Carbonation of Cement Stabilised Materials in Pavement Layers

by

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DECLARATION

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ABSTRACT

The remarkable increase in global traffic has encouraged innovative pavement designs capable of satisfying environmental, economic and social needs. The construction and demolition industry has had a major influence on the environment in terms of the amount of natural resources used as well as the high volume of waste produced. Landfills are being occupied at a steadfast rate, with an annual estimated 5-8 million tons of Construction Demolition Material (CDM) generated in South Africa, of which, approximately 1 million tons is concrete rubble. In developing countries, where natural resources are uncommon, sophisticated recycling and crushing techniques are implemented to produce high quality Recycled Concrete and Masonry Aggregate. South Africa is a country rich in Natural Aggregate (NA) which has conceivably led to limited exploration into the use of alternative sources aggregate.

Recycled Concrete Aggregate (RCA) and Recycled Concrete Masonry (RCM) has been used successfully in the application of pavement materials in other sectors of the world. However the full scope of RCA and RCM as a pavement material in South Africa is limited at this point in time as further knowledge pertaining to the recycling field and understanding of the behaviour and performance of these material is required. In understanding the behaviour and performance of RCA, it must first be determined whether this material would be characterised as a bound or unbound pavement material, or somewhere in between.

The scope of this research study aimed at gaining a better understanding of the durability issue most commonly associated with bound materials, known as carbonation. The experimental design incorporates the development of an accelerated lab carbonation procedure and implemented this by carbonating two types of RCA material with and without added cement. The two material types are distinguished by their grading which are continuous grade and gap grade. To better understand the influence of extrinsic and intrinsic properties on the carbonation potential of RCA, the two material types, with and without the addition of cement, were subjected to accelerated carbonation at curing times of 1, 7 and 28 days. Following the carbonation of the RCA material, the study undertook laboratory strength tests which include Unconfined Compressive Strength (UCS) tests as well as Indirect Tensile Strength Tests (ITS) and were performed on both non-carbonated and carbonated RCA material. The self-cementing potential of RCA was investigated by observing the results of the aforementioned tests and together with the outcome of carbonation, the material types were scrutinized in terms of their performance as a bound and/or unbound material as well as potential durability issues incurred as a measure against their extent of carbonation.

The carbonation results revealed that RCA material with 0% added cement, readily carbonates regardless of the curing time and grading of the material, which alludes to lightly cemented materials being more susceptible to carbonation.

RCA material with 2% added cement indicates greater resistance to carbonation but is inclined to be less resistant to carbonation as curing time is increased. Grading also had an influence on the resistance to carbonation when 2% cement was added to RCA, with continuous grade exhibiting higher resistance to carbonation than gap grade RCA.

A methodical analysis of the influence of variables (density, cement, moisture and grading) showed the interdependency and non-linearity of variables and correlation exist between this and UCS as a strength parameter to measure carbonation, but that the governing variable change with the strength development of the material.

The most important finding is the potential susceptibility of lightly stabilised materials to carbonation. It is imperative that guidelines are provided to mitigate these risks on the handling of these materials prior and during placement is provided to mitigate these risks.

ABSTRAK

Die merkwaardige verhoging in globale verkeer het aanleiding gegee tot meer innoverende plaveiselontwerpe wat beide meer ekonomiese, omgewings en sosiaal verantwoordelik is. Die konstruksie en demolisie industrie het ‘n groot impak op die omgewing in terme van die hoeveelheid natuurlike bronne wat deur hulle ontgin word, sowel as die hoë volume afval wat geskep word. Stortingsterreine word volgemaak teen ‘n kommerwekkende spoed, met ‘n jaarlikese tempo van tussen 5-8 million ton, vanwaar 1 miljoen ton betondemolisie is. In ontwikkellende lande, waar natuurlike bronne gewoonlik meer skaars is, word gesofistikeerde herwinning en breking tegnieke geimplimenteer om sodoende Herwinde Beton en Baksteen (HBB) te produseer. Suid-Afrika het aansienlik meer natuurlike bronne tot hulle beskikking wat tot minimale gebruik van alternatiewe bronne van aggregaat tot gevolg het.

Herwinde Beton (HB) en Herwinde Baksteen (HKB) is al suksesvol gebuik in ander sektore van die wêreld. Nietemin, hier in Suid-Afrika, en spesifiek in plaveislels, is die gebruik van HBB minimal as gevolg van onkunde oor die herwinningsveld en ‘n verstaan van die gedrag van die materiaal. In orde om die gedrag te verstaan, moet dit eers geidentifiseer word of die materiaal as ‘n “gebonde” of “ongebonde” materiaal gekaraktiseer moet word, of dalk iets tussenin.

Die omvang van die navorsingsstudie is om beter insigte oor die duursaamheid van die materiaal te verkry. Iets wat tipies gepaard gaan met gebonde materiale is karbonasie. Die eksperimentele ontwerp inkorporeer die ontwikkeling van ‘n versnelde lab karbonasie procedure, sowel as die gebruik van hierdie apparaat deur twee verskillende tipes HB, een sonder en een met sement. Die twee materiaal tipes word onderskei deur dat een ‘n kontinue gradering en die ander ‘n nie-kontinue gradering het. Om beter die eksterne en interne eienskappe wat karbonasie potensiaal op HB kan hê te verstaan, is die twee materiaal tipes, met en sonder sement, onderhewig aan die versnelde laboratorium karbonasie proses gesit vir monsters wat 1,7 en 28 dae gekuur is. Nalope hierdie toetse, was die onbeperkte sterkte (UCS) en die indirekte trektoets (ITS) gedoen op beide nie-gekarboneerde en gekarboneerde HB materiaal. Die self-sementering potensiaal van HB was ook ondersoek deur die resultate te analiseer samehangende met die uitkomstes van karbonasie. Materiaal tipes was ook ondersoek vir hulle gedrag in terme van ‘n gebonde of ongebonde materiaal sowel as die vatbaarheid agv die graad van karbonasie.

Die karbonasie resultate het gewys dat HB materiaal met geen addisionele sement, maklik karboneer ongeag van die kuringtyd en gradering van die materiaal en wys dus dat moontlik ligte gesementeerde materiaal meer vatbaar is vir die karboneringproses. HB met 2% was meer bestand teen die karbonasie proses, maar hierdie verminder met kuringtyd. ‘n Kontinue gradering HB wys na ‘n hoër bestandheid teen karbonasie as dit van ‘n nie-kontinue gradering.

‘n Metodiese analise van die verskillende faktore (dightheid, sement, vog, gradering) het uitgewys dat hierdie faktore afhankilik van mekaar is, sowel as dat daar ‘n nie-liniere korelasie tussen hulle en die onbeprekte druk sterkte bestaan.

Die mees belangrikste bevinding is dat die potensiaal van vatbaarheid vir ligte gesementeerde materiaal. Dit is noodsaaklik dat riglyne ontwikkel op die hantering van hierdie materiaal voor en met plasing word om risiko te verminder.

ACKNOWLEDGMENTS

One day, in retrospect,

The years of struggle

Will strike you as the most beautiful.

-Sigmund Freud-

With these words in mind, I want to show my sincere gratitude and appreciation to the people in my life who stood by me through this journey and supported me from the beginning to the very end. Mostly, for being a part of these past 'beautiful' years.

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To my brother, Shane for being the true definition of strength and endurance, you are a superhero. My beautiful sisters, Roxanne and Daniella, you make my life a happy and joyful place. I am grateful every day to have been blessed with the amazing siblings I have.

Lastly, but in no way least, thank you to my fellow academics, Nina Agnello, Zaandré Brekenkamp and Elaine Goosen. You were all an inspiration and a force to be reckoned with over the past years.

Finally, I would like to dedicate my thesis to my family and my boyfriend, Werner Gaigher.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

AFt:	Ettringite
AFm:	Monosulphate
AASHTO:	American Association of Highway and Transportation Officials
CDW:	Crushed Demolition Waste
CO_2:	Carbon Dioxide
CRCA:	Coarse Recycled Concrete Aggregate
CH:	Calcium Hydroxide
CSH:	Calcium Silicate Hydrate
C_2S:	Belite
C_3S:	Alite
DD:	Dry Density
FRCA:	Fine Recycled Concrete Aggregate
HCL:	Hydrochloric Acid
ITS:	Indirect Tensile Strength
ITZ:	Interfacial Transition Zone
MC:	Moisture Content
MC_H:	Hygroscopic Moisture Content
NA:	Natural Aggregate
OMC:	Optimum Moisture Content
P:	Pressure
PD:	Permanent Deformation
PP_{CO2}:	Partial Pressure of CO_2
RA:	Recycled Aggregate
RAC:	Recycled Aggregate Concrete

RACLA:	Research Accelerated Carbonation Lab Apparatus
RCA:	Recycled Concrete Aggregate
RH:	Relative Humidity
SAMDM:	South African Mechanistic Design
SAPEM:	South African Pavement Engineering Manual
SEM:	Scanning Electron Microscopy
TGA:	Thermogravimetry Analysis
TRH:	Technical Recommendations for Highways
TSA:	Total Surface Area
UCS:	Unconfined Compressive Strength
UGM:	Unbound Granular Material
WA:	Water Absorption
XRD:	X-Ray Diffraction
x:	Carbonation Depth

CHAPTER 1: INTRODUCTION

A significant amount of natural resources is used by the road construction industry as bound and unbound granular materials in the application of pavement layers. The utilisation of alternative road materials has become necessary due to the rapid depletion of these natural sources. In many countries the belief in sustainable application of construction materials has lead to advances in technology in the use/re-use of alternative secondary materials. South Africa is no different in that there is an ardent drive in recognising and applying more sustainable practices. Some of these examples include material technologies such as Bitumen Stabilised Materials, the advances in Enrobés à Module Elevé (due to its potential to design a perpetual pavement) and many other successful applications. One such material which has significant potential in the application of pavement layers is the use of Construction Demolition Material (CDM). Despite the interest by which these new materials are embraced there are still many questions that need to be articulated into the guidance and the application of such a technology. Some performance aspects are well known and very well researched and the most comprehensive in its nature has been published by (Van Niekerk, 2002)

Apart from CDM providing satisfactory results in its application as a granular layer (if processed correctly), numerous research studies refer to the “self-cementing” properties of the material. In this sense, the material with or without the addition of cement is accepted to perform as a lightly bound pavement layer. The benefits of such a layer is well known and includes the development of increased strength over time. However, alluding to this benefit and capitalising on its full capacity are two different matters entirely. With this advantage, come some of the drawbacks associated with bound material layers such as shrinkage cracking, premature decreased stiffness (durability issues) and apparent recrudescence in its pavement life.

One of the causes of shrinkage cracking is carbonation. Carbonation is a chemical reaction in which Carbon Dioxide (CO_2) reacts with products formed through the hydration of cement, the main participant being Calcium Hydroxide. This reaction takes place within the pores, and results in the deposition of Calcium Carbonate ($CaCO_3$) precipitate. Simultaneously, a number of compounds decompose as a result of this reaction, included in these compounds are the depletion and destruction $Ca(OH)_2$ and Magnesium Hydroxide $Mg(OH)_2$ (Claisse *et al.*, 1999). The most significant result of these reactions is a decrease in pH from 12.4 to below 8.3. Other factors which are affected is the solubility hydration products, and more importantly the relative density of the material (Paige-Green, Netterburg and Sampson, 1990).

It is understandable that these consequences of carbonation could be detrimental due to the loss of strength and the fatigue life of a pavement layer. Carbonation then manifests in practical terms as (a) surface weakening caused by firstly the disintegration of the surface layer and consequently punching chippings and bleeding and/or (b) the loss of cementation evolving from the bottom of the layer and ultimately leading to progressive in-service loss (Paige-Green, Netterburg and Sampson, 1990).

Yet, articulating carbonation in practice, and the factors at play in a quantifiable manner still remains a challenge. Nonetheless, the thought process on this has evolved and has been a progressive understanding. The original assumption included the cause of the weakening of a stabilised layer could be caused by soluble salt damage, over-compaction and weathering or insufficient lime content and the carbonation concept not explicitly identified as a cause of failure. However, Netterberg and Paige-Green (2009) articulated that an important consequence was found that the carbonation occurred during curing and that the subsequent exposure to the atmosphere prior to sealing, even after a prime coat was applied could lead to further carbonation and disintegration. A general finding on the impact of carbonation was that the progressive loss of strength was on average 40% of the original uniaxial compressive strength, regardless of the addition and type of stabiliser. They also identified that the largest cause of carbonation appeared to be extrinsic, including that the most rapid carbonation happened at relative humidity of about 50% and magnitude of exposure of CO_2. However, taking cognisance of the extrinsic factors (which can only be controlled in limited ways in construction) the role of intrinsic factors are important and an understanding of these variables lead to improved understanding of contributing factors.

Recognising the challenges of bound materials while considering the behaviour of RCA as that of a lightly bound material, the question is if carbonation could manifest as an issue and if so would it be quantifiable? In effect, cement content, moisture content and material grading could play a vital role when considering the potential durability issues of RCA. At the same time it is understood that environmental factors (relative humidity, surface area, CO_2 exposure and concentration) play an equally important role. The main objective remains dedicated to RCA's susceptibility to carbonation, however, overall the research is of benefit to the performance of bound pavement materials in general.

1.1 Research Objectives

The primary objective of this research study is to gain better understanding of the influence of carbonation on bound materials including materials that have self-cementing potential.

In order to achieve the primary objective, secondary objectives have been identified:

- Understanding the intrinsic and extrinsic factors that contribute to the carbonation process in order to develop and understanding how these mechanisms manifest within the pavement layer.
- Investigate and develop a method that would simulate carbonation in laboratory conditions at an accelerated rate and evaluate the effect of carbonation on RCA.
- To analyse results and determine how carbonation influences strength characteristics of RCA.
- To develop correlations between the governing variables and carbonation and ultimately identify this influence on the pavement life of a material.

1.2 Research Limitations

The research focusses on the intrinsic mix variables that could play a role in the degree of carbonation. Environmental factors (such as relative humidity and CO_2 exposure) will not be varied and are not included in the experimental work of this research. The research also does not aim to correlate the lab results with on-site conditions. This will entail a further phase not addressed in this particular project.

1.3 Report Layout

This thesis report includes seven chapters, and the layout briefly discussed here:

- Chapter 1 includes an introduction and brief background on the challenge of carbonation. From this background objectives are identified and the structure of the report provided.
- Chapter 2 includes a literature review on stabilised materials and the mechanisms of carbonation including the influence the performance of RCA as pavement material.
- Chapter 3 describes the outline of the research methodology including lab experimental work. The material preparation and the development of carbonation equipment is also explained.
- Chapter 4 includes the analysis of results obtained from laboratory work including the evaluation of different intrinsic variables on the carbonation process;

- Chapter 5 is the synthesising of these results into correlation and articulation into strength as a characteristic which gives identification to the pavement life;
- Chapter 6 concludes with a summary of the findings research and discusses the outcomes of the project providing recommendations on using this material in a pavement structure.
- Chapter 7 presents the conclusions and recommendations for further research.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Research on the application of RCA as a road material in South Africa has caught traction in recent years, specifically as prominence is placed on recycling worldwide. However, specifications for the use of this material is a developing process in South Africa as the behaviour and durability is still not fully understood. This is partly due to the fact of categorising the material as either a granular material or a cemented material. The reality is that the behaviour of RCA possibly falls somewhere in between these two material types, as schematically illustrated in Figure 2-1. The main reason for this discrepancy is attributed to the presence of remnants of latent adhered mortar remain attached to the original aggregate.

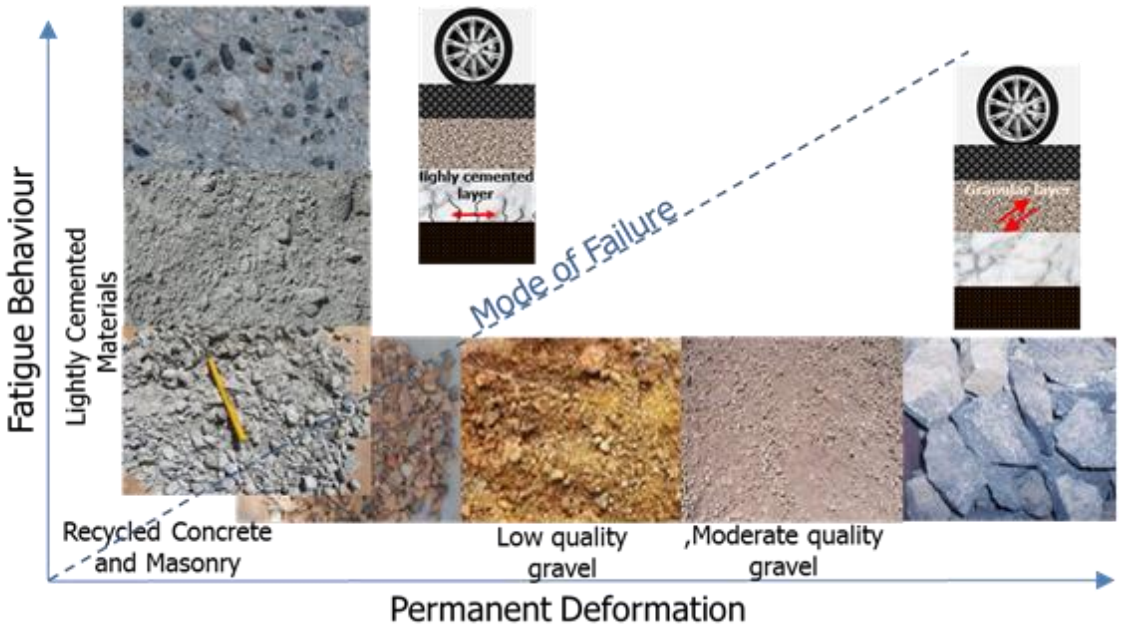


Figure 2-1: Typical Schematic Illustration on the Potential Modes of Failure for Recycled Concrete Aggregate in Pavement Layers (Rudman and Jenkins, 2015)

This chapter focuses on the behaviour of RCA relative to both that of cemented materials and granular materials. The major durability issue of cemented materials, namely carbonation, is scrutinised and it is seen if this is a necessary issue to be considered for RCA.

With the purpose of addressing these questions, the literature study will firstly focus on a brief overview of how South African pavement layers are composed in comparison to the rest of the world. This is an important point to highlight as the structural significance of South African granular and cemented pavement layers varies from that of other countries as a result of the placement of these layers within the pavement structure. Secondly, the typical behaviour of both materials are discussed with strong focus on cemented materials and related issues such

as the importance to not overlook carbonation. As a final point, the behaviour of RCA is placed into context in relation to the reported behaviour of granular and cemented pavement materials. Following the discussion of these three pavement materials and the susceptibility of RCA to carbonation (even without the addition of stabiliser) is brought forward, issues and factors that influence carbonation are identified for a complete comprehension of this durability concern.

2.2 Pavement Layer Materials

2.2.1 South African Pavement Design

Roads have evolved from modest sparse networks of tracks to advanced designed pavement structures. To begin with, roads were built based on experience, with the Romans being accredited as the best road builders of the remote ages. Through the ages, road design has become more sophisticated and technical as the functional requirements reached new high demands mainly due to an increase in travelling.

In the 20th century, the improved sophisticated pavement design approach is founded on empirical and/or mechanistic specifications. A typical pavement structure includes a combination of selected layered materials and subgrade. The type of material used to construct the upper layers together with the surfacing determines the classification of a pavement structure as either flexible or rigid. In both cases, the layers are designed to endure and withstand applicable traffic demands and particular environmental conditions over the pavement design period.

Generally two types of flexible pavement structures are used globally. The main difference being the thickness of the asphalt surfacing layer. Figure 2-2 illustrates the fundamental difference between a typical South African pavement design and that of other countries.

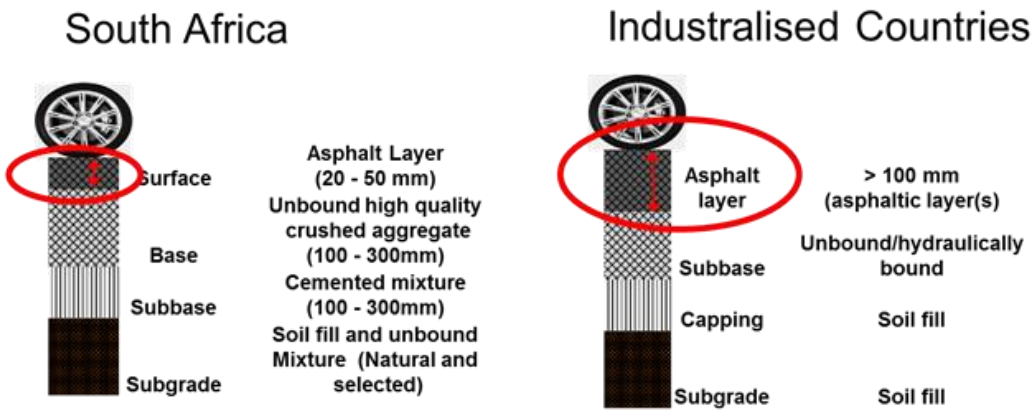


Figure 2-2: A Typical South African Flexible Pavement Design Compared to that of Other Countries (Rudman et. al., 2017)

A typical South African flexible pavement design consists of a relatively thin asphalt surfacing with a thick granular base layer. This pavement type is commonly referred to as the 'inverted' flexible pavement as it consists of a stabilised subbase layer. The individual pavement layers are designed to balance adequate material stiffnesses so that induced stresses and strains are optimally balanced through each of the pavement layers. To ensure that the pavement layers maintain a balanced state, the design approach comprises of placing the neutral axis well below the granular layer. This is as a result of the granular layer performing as a stress dependent material, i.e. the granular pavement layer will increase in stiffness when the confinement of this layer is increased. To compliment this behaviour, the subbase layer which is comprised of a cemented material, will resist the developing tensile stresses at the bottom of the layer.

Placing of these material types in this order provides a balanced pavement structure as the granular layer contributes to dissipating the stresses induced by traffic loading. This results in minimising the magnitude of these induced stresses being transferred to the lower subbase layers and the underlying subgrade layer. This confirms that the closer a material is placed to the surface of a pavement structure, the higher the expected demand will be on their performance. Durability issues, such as carbonation, hinders the performance of the material layer as it encourages early deterioration of the material and as a result, the pavement structure will fail to fulfil its intended function.

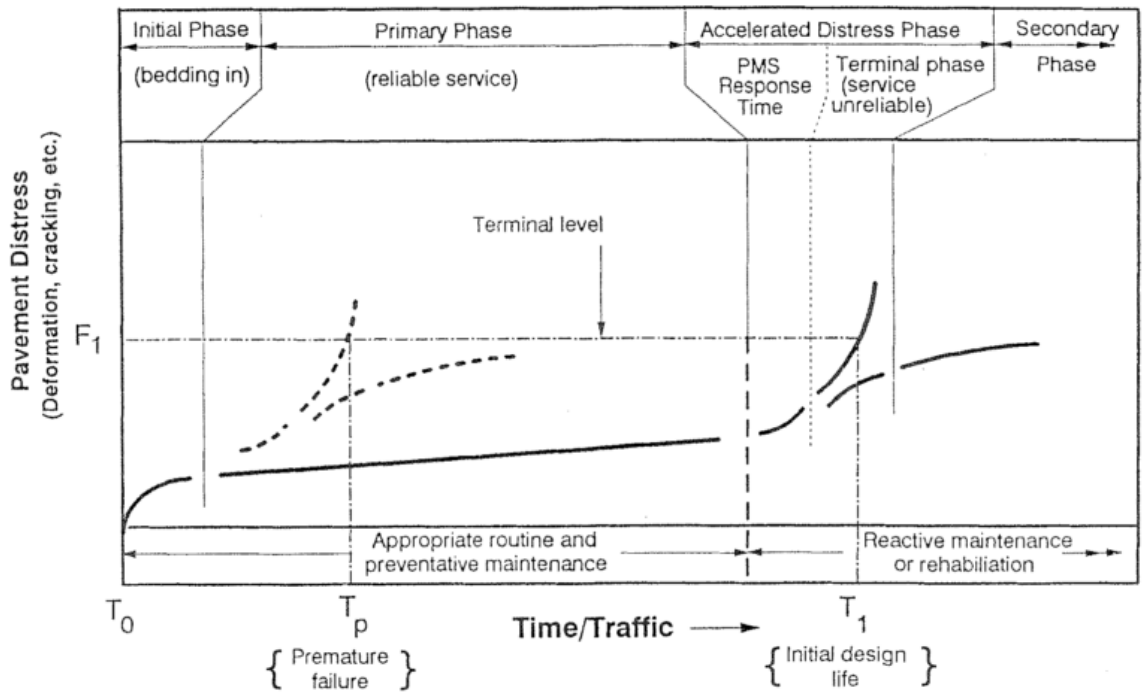


Figure 2-3: General Behaviour of Flexible Pavement (TRH4, 1996)

When the stresses and strains induced by the pavement structure breach the bearing capacity of a material layer, the pavement structure will deteriorate. In Figure 2-3 the general behaviour of a flexible pavement is presented and illustrates the influence of various mechanisms of failure on the pavement life.

Traffic loads and environmental conditions are the major source of stresses and strains induced within pavement layers. Material behaviour is classified according to their response to these stresses and strains and failure to endure them will lead to early deterioration of the pavement structure. The South African Mechanistic-Empirical Design Method (SAMDM) is one of the methods that can be used in the flexible pavement design procedure (Theyse, 2001). Understanding the fundamental approach of the SAMDM provides insight on how various material types and their associated behaviours are measured, even in the general form.

In flexible pavements, the SAMDM normally splits resilient pavement response and permanent pavement response and capture these characteristics in the Resilient Modulus (M_r) model and the distress models, respectively. Figure 2-4 illustrates the position of critical stresses and strains of various material layers within a flexible pavement structure.

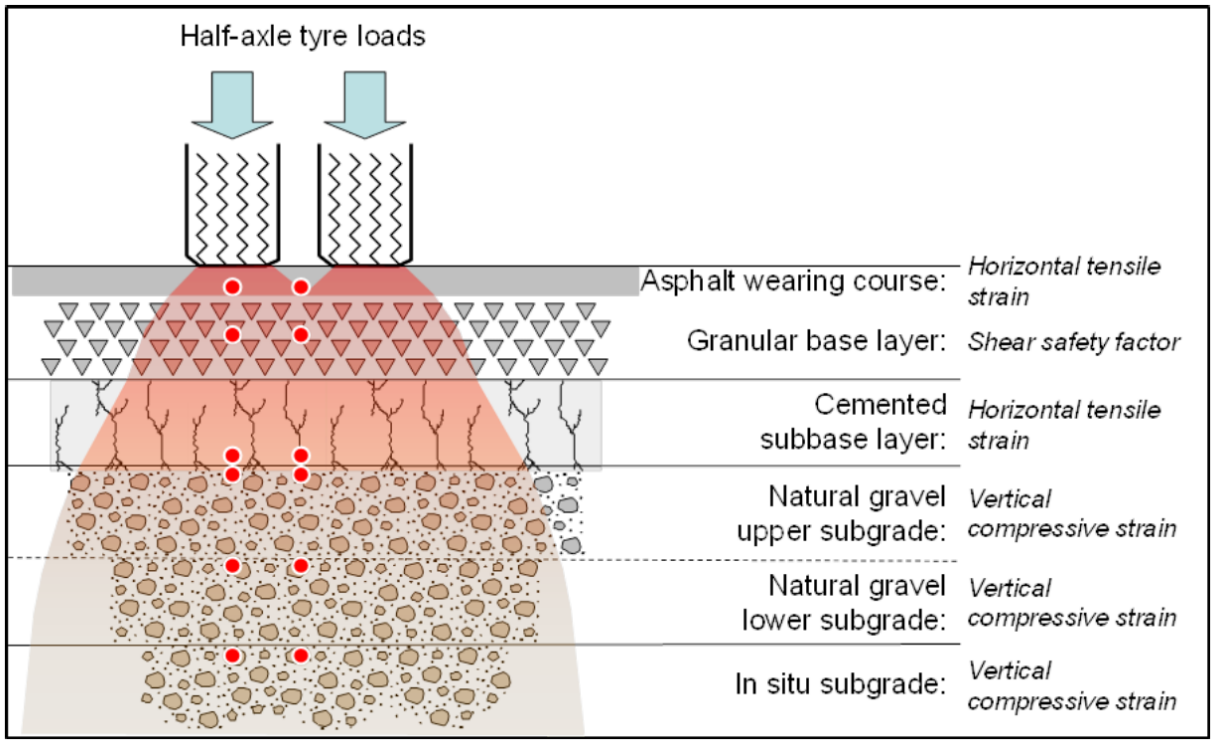


Figure 2-4: Analysis Positions for Critical Stress and Strain Parameters (SAPEM, 2014)

Depending on the material type and the location within the pavement structure, the position of critical stresses and strains are identified. These critical parameters, together with other numerical input values applied to various models are combined to develop a transfer function. Transfer functions form the empirical components of the SAMDM and give an indication of the number of stress and strain repetitions a pavement structure is capable of sustaining before a terminal condition is reached.

Based on stress and strain calculations, together with Figure 2-4 above, the following important pavement behaviour (and failure) criteria can be identified as (SAPEM, 2014):

- Horizontal tensile stress/strain in asphalt layer (fatigue)
- Horizontal tensile stress/strain in cemented layer (fatigue)
- Vertical compressive stress/strain on subgrade (permanent deformation)
- Vertical compressive stress on cemented layer (crushing)
- Three dimensional stress condition in granular layer (failure, permanent deformation)
- Permanent deformation in asphalt layer

The most important of these behaviour responses, in the current context, is that of the granular and cemented layers. Noticeably, the performance of a pavement structure is directly dependent on the performance properties of the type of material. Thus, it is essential to understand the performance of different types of pavement materials and how they influence the overall pavement design.

2.3 Types of Pavement Materials

Several material classification systems have been developed based on either visual inspection of the material itself or test results thereof.

Pavement materials can be classified into two main groups, namely:

- Granular and Cemented Materials
- Bitumen and Asphalt Materials

In South Africa, the Technical Recommendations for Highways (TRH) classification system is widely used (SAPEM, 2014) and the use of granular and cemented material in flexible pavements is most common. For the purpose of this research study, the performance properties of these two materials will be discussed, followed by a brief introduction to recycled concrete material.

2.3.1 Granular (Unbound) Materials

Unbound granular material's (UGM's) include natural gravels and granular materials. Classification of these materials are as follows (TRH14, 2013):

- **Graded crushed stone**: G1, G2, G3
- **Natural gravels** (including modified and processed gravel): G4, G5, G6
- **Gravel-soil:** G7, G8, G9, G10

This classification system is generally dependent on a number of requirements such as grading, Atterberg limits and bearing strength. Graded crushed stone forms the skeleton of the pavement, giving it its structure (Jenkins and Rudman, 2016). Where a G1 material is expected to fall within the most stringent requirements, there is slightly more tolerance when classifying a G2 and G3 material. This leniency is extended right to the lowest class of granular materials, namely a G10. Table 2-1 represents the requirements specified by THR14 (2013) for G1 to G10 materials.

Table 2-1: Specifications for Various Unbound Pavement Materials (Jenkins, 2013)

Groups	G1, G2, G3: Graded Crushed Stone			G4, G5, G6: Natural Gravels			G7, G8, G9, G10: Gravel Soil			
Description	G1 Crushed unweathered rock.	G2, G3, Crushed rock, boulders or coarse gravel.		Natural gravel: may be mixed with crushed rock such as boulders. May be cementitiously or mechanically modified.			Categorised in terms of properties below.			
Material Class	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10
GRADING										
Sieve Size (mm)	Nominal max size 37.5 mm[1]	Nominal max size 28 (26.5) mm[1]			Max size 64 mm or two-thirds of compacted layer thickness, whichever is smaller		Max size in place, after compaction, shall not be greater than two-thirds of the layer thickness	No grading requirements.		
50/53	100			100						
37.5	100			85 - 100						
28/26.5	84 – 94	100		-						
20/19	71 – 84	85 – 95		60 - 90						
14/13.2	59 – 75	71 – 84		-						
5/4.75	36 – 53	42 – 60		30 - 65						
2	23 – 40	27 – 45		20 - 50						
0.425	11 – 24	13 – 27		10 - 30						
0.075	4 - 12	5 - 12		5 - 15						
Grading Modulus (min)	n/a			n/a	1.5	1.2	n/a			
Flakiness Index	Max 35% on weighted average of -28 (26.5) and -20 (19) mm fractions		n/a	n/a			n/a			
Crushing Strength	10% FACT (min) 110kN or ACV (max) 29%		n/a	n/a			n/a			
ATTERBERG LIMITS										
Liquid Limit (max)	25	25		25	30	n/a	n/a	No Atterberg Limit requirements		
Plasticity Index, PI (max)	4	6		6	10	12 or 3 GM[2] +10	12 or 3 GM[2] +10			
Linear shrinkage, % (max)	4	3		3	5	n/a	n/a			
Linear shrinkage x -0.425 mm sieve (max)[2]	n/a			170	170	n/a	n/a			
BEARING STRENGTH AND SWELL										
CBR, % (min) at MDD[4]	n/a	80 at 98%		80 at 98%	45 at 95% [5]	25 at 93%	15 at 93%	10 at in situ	7 at in situ	3 at in situ
Swell, % (max) at MDD	n/a	0.2 at 100%		0.2 at 100%	0.5 at 100%	1.0%	1.5%			
Material Class	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10

Notes:

1. G1 adjustments to grading can only be made using crusher dust or other fractions from the parent rock. Only in exceptional cases can a maximum 10% non-plastic fines be added. G2 and G3 may be a blend of crushed stone and other fine aggregate to adjust the grading.
2. GM is the gading modulus
3. Only applicable to modular calcretes
4. MDD is the maximum dry density determined by the modified AASHTO method.
5. In dry areas (Weinert N > 10) and AADT < 300 CBR can reduced to 25% @ 95% MDD if subbase cover is at least 150mm.

It can be said that unbound materials are the core component in flexible pavement structures as they generally serve to provide a working platform, drainage layers and structural layers for the pavement system. The application of unbound materials within a pavement structure and, hence, the expected material performance are key parameters when selecting the material class to be used. Typically, the higher class materials, G1, G2 and G3, are used in the base layer of a pavement structure. Whereas, the lower class materials, G4 - G10 are more suitable for use in the lower pavement layers such as the subbase and subgrade.

2.3.1.1 Behaviour of Unbound Granular Materials

Understanding of material behaviour is critical as this needs to be considered during the pavement design strategy. Material behaviour is categorised based on a materials response which can be elastic, plastic, viscose, or a combination of all of these. All Granular materials show a stress dependent behaviour and respond elastically up until the elastic limit is reached, where after they respond plastically. This behaviour response is referred to as elasto-plastic and is modelled as illustrated in Figure 2-5.

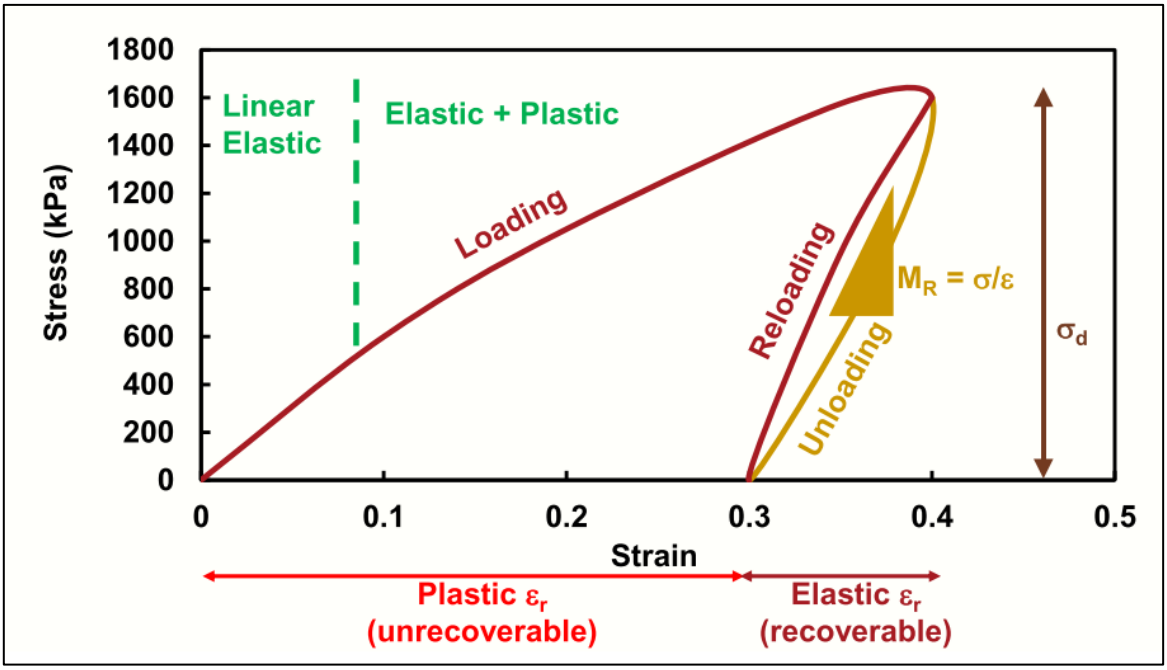


Figure 2-5: Elasto-plastic Behaviour and Resilient Modulus (SAPEM, 2014)

Each load repetition, within the plastic zone, accumulates some plastic strain, resulting in non-recoverable (plastic) strain which manifests as permanent deformation of the material. The primary cause of failure within an unbound granular layer is attributed to shear. A materials capacity to resist shear is a function of the aggregate skeleton. When the voids of an aggregate skeleton are filled with purely fine particles, grain-to-grain contact of the coarse particles are able to perform well in response to the abrasive action of the applied wheel loads. The fine

particles act to increase resistance against deformation and together, this combination results in maximum density of the material.

The behaviour of UGMs is dependent on the material characteristics such as strength, stiffness and permanent deformation. The most important factors that influence these characteristics include:

- stress conditions
- material gradation
- aggregate angularity
- type of material
- degree of compaction
- moisture content

The most important variable with regards to all aspects of pavement material behaviour, is a form of mechanical stabilisation known as compaction. The process of compaction is fundamental to ensure the best possible performance of a gravel or soil as it increases the density of the material and reduces the volume of air within the material structure. Compaction has a direct influence on the following material properties (SAPEM, 2014):

- stiffness (load spreading)
- shear strength
- bearing capacity
- permeability
- porosity

The aggregate skeleton has a major influence on the ease of compaction, Figure 2-6 summarises this relationship.

(a) Aggregate with no fines	(b) Aggregate with sufficient fines for maximum density	(c) Aggregate with great amount of fines
Grain-to-grain contact	Grain-to-grain contact With increased resistance Against deformation	Grain-to-grain contact destroyed, aggregate 'floating' in soil
Variable density	Increased density	Decreased density
Pervious	Practically impervious	Practically impervious
Non-frost-susceptible	Frost-susceptible	Frost-susceptible
High stability if Confined, low if Unconfined	High stability in confined or unconfined conditions	Low stability
Not affected by Adverse water condition	Not affected by adverse water condition	Greatly affected by adverse water condition
Very difficult to compact	Moderately difficult to compact	Not difficult to compact

Figure 2-6: Three Physical States of Soil-aggregate mixtures (Molenaar, 2015)

UGM's are composed of either crushed rock or natural gravel aggregate. Natural aggregates can often be sourced from local borrow pits where quality control can prove to be a challenge. Established quarry's produce crushed rock aggregate under well monitored operations. The rock is extracted from the earth by blasting, thereafter it is broken down into more manageable sizes, crushed and screened. Crushed rock clearly produces a higher quality aggregate, however, production and transport costs appeal to the use of natural aggregates instead.

Higher aggregate quality of UGM's result in better aggregate interlocking within the aggregate skeleton and the friction caused by aggregate interlocking encourages better shear resistance of the UGM.

Failure of an unbound pavement layer results in the following failure distresses:

- Fatigue cracking
- Rutting and deformations
- Shear deformations

These form the performance parameters of UGM's. The limitations of these performance parameters can be improved by adding a small amount of chemical stabiliser to the material, this material is commonly referred to as a bound material.

2.3.2 Bound Granular Materials

Bound granular materials are used extensively throughout South Africa, particularly as subbase materials. Properties of bound materials are largely based on the direct strength tests, Unconfined Compressive Strength (UCS) and Indirect Tensile Strength (ITS). The ITS test is a poor indicator of durability and early UCS tests (for example, at 7 days curing) gives little to no indication of durability as the material is expected to further disintegrate with time. Nevertheless, the classification of bound materials are dependent on their strength performance as shown in Table 2-2.

Table 2-2: Specification for Stabilised Materials (TRH13, 1986 and TRH14, 2013)

Classification	UCS @ 7 days at 100% Mod AASHTO Compaction [MPa]	UCS @ 7 days at 97% Mod AASHTO Compaction [MPa]
C1	6 – 12	4 – 8
C2	3 – 6	2 – 4
C3	1.5 – 3	1 – 2
C4	0.75 – 1.5	0.5 - 1
	Minimum ITS [kPa]	
C3	200	
C4	120	

'Modification' or 'stabilisation' of UGM's produces a bound granular material with improved properties. The modification process involves the addition of a small amount of chemical stabiliser, such as lime or cement, to material. Modification improves material properties and can slightly increase the compressive strength of a material. In some cases, an increase in structural capacity is necessary, for this the addition of a larger amount of chemical stabiliser is added, a process termed 'stabilisation'. A seven-day compressive strength of 0.8MPa has been suggested as the suitable boundary between modification and stabilisation (Gourley and Greening, 1999). For the purpose of this research study, the stabilisation process will be considered and is also discussed in further detail in Section 2.7.

In general, stabilisation of UGMs ensure the following advantages (SAPEM, 2014):

- Increased compressive and tensile strengths
- Increases stiffness (Mr) of the material
- Improvement of durability (mostly resistance against effects of moisture)
- Improved workability of clay materials
- Reduced in situ moisture content

Due to their popularity and positive advantages, noted above, a stabilisation guideline (TRH13, 1986) has been established in South Africa.

2.3.2.1 Select Chemical Stabiliser

The chemical stabiliser used for stabilisation can be that of lime or cement. Different reactions take place based on the choice of chemical stabiliser. The rate of these reactions are dependent on the chemical composition of the chosen stabiliser, aggregate properties and environmental conditions (such as temperature and pressure) at time of mixing.

Lime is simply calcium oxide (or quicklime), whereas, cement comprises calcium silicates and aluminates, and calcium oxide (Gourley and Greening, 1999). The choice of stabiliser is dependent on physical properties of the material as well as the purpose of stabilisation.

Cement improves material properties such as strength, fatigue and cracking, while lime improves strength, decreases plasticity and increases the pH of the material. Figure 2-7 shows the type of stabilization with lime or cement (Xuan, 2012).

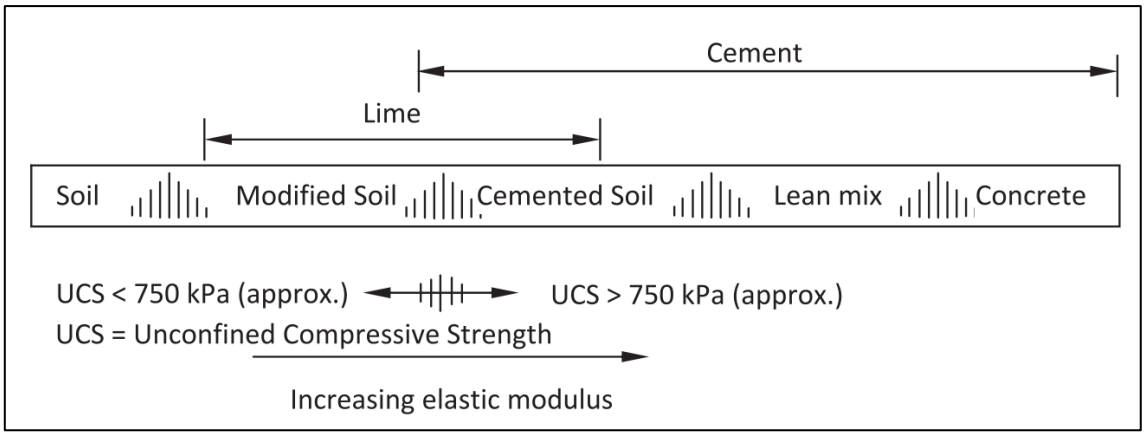


Figure 2-7: Types of Stabilization with Lime and Cement (Xuan, 2012)

Cement stabilisation is applicable to most material types, however, high contents are needed to treat clayey materials. Pulverizing and thorough mixing of clayey materials with high quantities of cement is problematic and therefore, lime is a better choice for stabilisation of fine clayed materials (Xuan, 2012). Material type and particle size must be carefully considered before the type of chemical stabiliser is selected. Figure 2-7 together with

Table 2-3 below can be used as a guide to choosing a suitable chemical stabilizer.

Table 2-3: Stabilizing Modes of Soils (Xuan, 2012)

Designation	Fine clays	Coarse clays	Fine silts	Coarse silts	Fine sands	Coarse sand	Aggregate
Particle size (mm)	<0.0006	0.0006-0.002	0.002-0.01	0.01-0.06	0.06-0.4	0.4-2.0	>2.0
Volume stability	Very Poor	Fair	Fair	Good	Very Good		
Stabilizing agent: Lime							
Stabilizing agent: Cement							
Stabilizing agent: Bitumen							

Range of maximum efficiency

Effective, but quality control is difficult

Stabilisation is not always permanent and the chemical reactions can be reversed. This results in loss of stabilisation and is due to the instability of the reaction products. It has been shown that the reaction products are stable when a pH value of 12.4 is maintained within the material. Further explanation of the chemical reactions which take place during stabilization is described in Section 2.7.

2.3.2.2 Behaviour of Bound Granular Materials

Bound materials respond elastically to loading and can be described as a semi-rigid material. This means that no permanent deformation occurs. Subjecting bound materials to repetitive loading while they are within their elastic range, provided that they are not loaded beyond their yield stress and/or strain (where microcracking is initiated), the material will remain intact indefinitely. This material state is not easily maintained and it is best to accept that these materials will always crack and cannot be avoided but should rather be considered as a feature of the stabilisation process (TRH13, 1986).

As with unbound granular materials, the SAMDM is used to evaluate bound material layers. Depending on the position of the bound layer within the pavement structure, the position and type of critical parameters differ (refer to Figure 2-4). The critical position for a cemented (bound) subbase is at the top and bottom of the layer where crushing and fatigue failure occurs, respectively. Terminal failure of a cemented subbase follows three phases of cracking. The first phase is referred to as the pre-cracked phase and does not include cracks associated with traffic. Instead, the cracks occur as a result of shrinkage of the stabilised material. The second phase, the transitional phase, includes micro-cracks induced by traffic loads however, at this phase the material layer is still intact. The final, post-cracked phase results in a broken material layer and it is at this point that the (previously) cemented layer deteriorates and subsequently behaves as an equivalent granular layer.

Figure 2-8 illustrates the formation of shrinkage cracks in a bound material and can be summed in terms of the stress and strength of the material over time. When the tensile stress of the material exceeds the material strength, at an early age, numerous narrow and closely spaced cracks are formed. On the other hand, when the tensile stress exceeds the material stress, at a later stage, fewer cracks that are wider and placed further apart. Shrinkage cracks can be avoided as long as the material strength exceeds the tensile strength of the material induced by shrinkage.

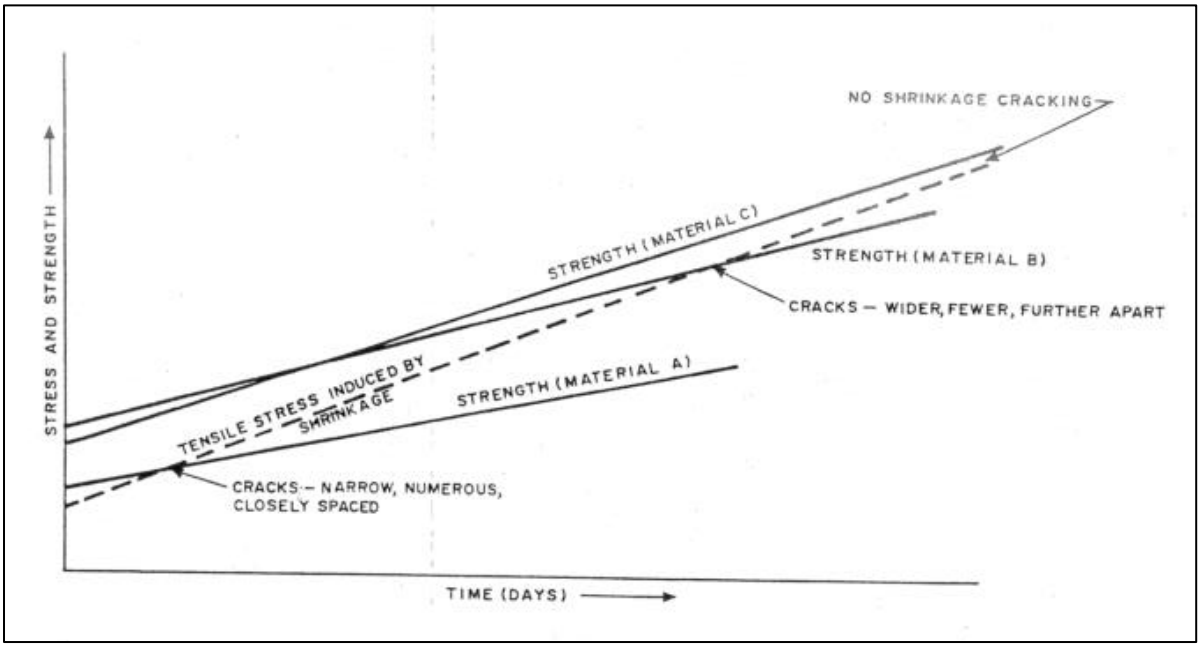


Figure 2-8: Cracking as a result of the interrelationship between shrinkage stress, strength and time (TRH 13, 1986)

These cracking phases are attributed to the brittle nature of bound granular materials and can be grouped as shrinkage cracks or fatigue cracks. The development of these cracks occur due to traffic overloading and exposure to severe climate conditions which affects the serviceability of the pavement structure. A materials inability to remain serviceable for the design life of the pavement structure is directly related to the durability of the material. Bound granular materials, specifically, are susceptible to poor durability and carbonation is considered to be the predominant cause thereof (Netterberg and Paige-Green, 1984). In fact, carbonation causes additional shrinkage, commonly referred to as carbonation shrinkage.

(Chen, Thomas and Jennings, 2006) suggested that carbonation shrinkage is a special case of decalcification shrinkage and is governed by the decrease in Ca/Si ratio which accompanies the carbonation of Calcium Silicate Hydrate (CSH). Furthermore, cracking is proposed to be influenced by the gradient of Ca/Si ratios across the specimen and as a result of Portland cements lower CH content, it is deemed more vulnerable to carbonation cracking (Chen,

Thomas and Jennings, 2006). Carbonation induced cracking has been observed in multiple studies. Šavija & Luković (2016) cites the findings of Han *et al.* (2012)which showed significant cracking in Portland cement paste and found that carbonation was accelerated close to the crack tip which concurs well with Chen et al. (2006). A 3D image of the carbonation cracks of Portland cement is shown in Figure 2-9.

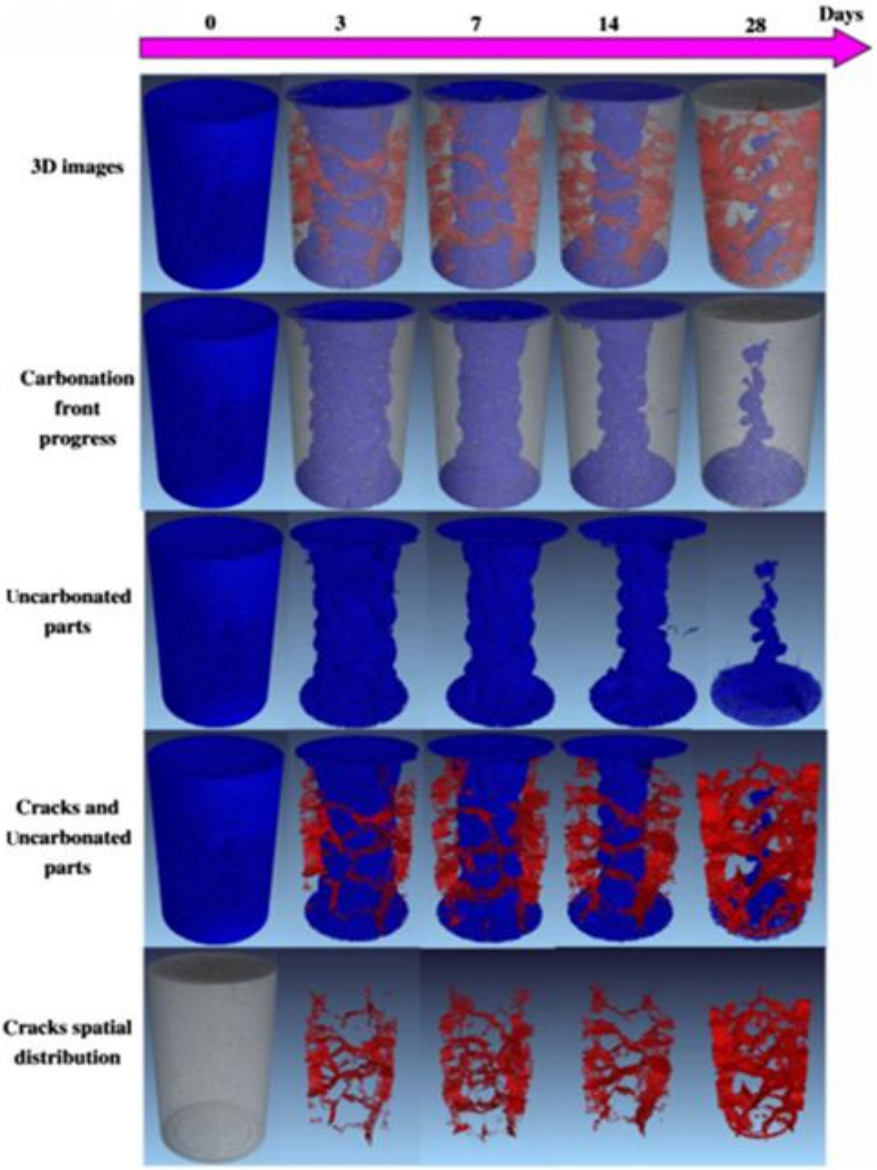


Figure 2-9: 3D Images of Carbonation Front Progress and Cracks Spatial Distribution with Different Carbonation Times (Šavija and Luković, 2016)

Figure 2-10: Effect of Carbonation Adjacent to Cracks in a Stabilized Layer (SAPEM, 2014)

In terms of pavements, this occurrence has been indicated in the field. The carbonation in Figure 2-10, is indicated by the colourless material neighbouring the crack patterns in the pavement material. This is a typical indication of carbonation where the reaction of the material sprayed with phenolphthalein indicator appears colourless. The material which appears fuchsia-pink confirms that active cement products are still present and the pH of the material is above a value. Carbonation is discussed in further detail in Section 2.8.

2.4 Durability of Pavement Materials

In a general sense, the term ‘durability’ refers to the ability to persist, last, not change and be everlasting. In terms of pavement materials, durability can be described as the ability of a material to remain serviceable for at least the design life of the structure as illustrated in Figure 2-11.

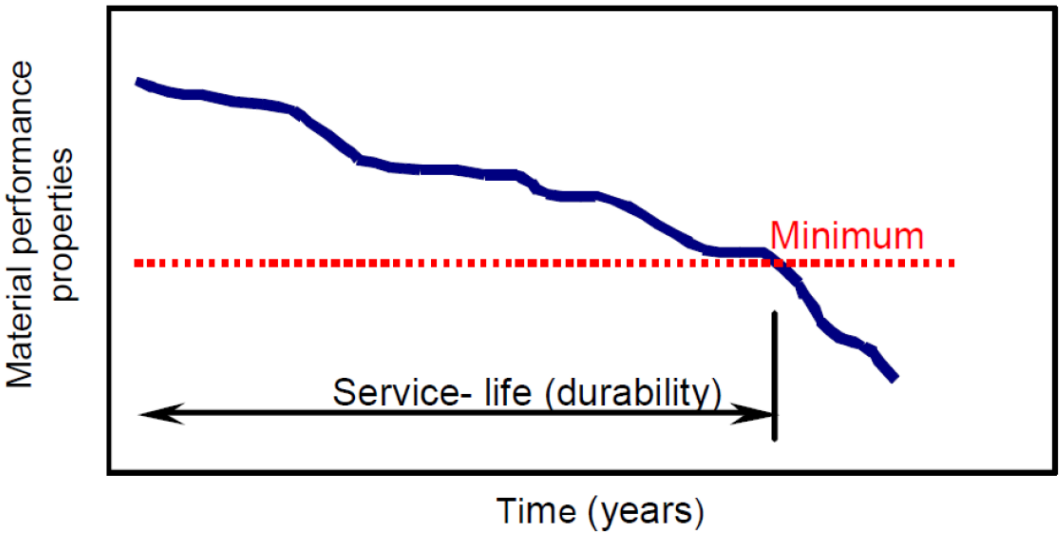


Figure 2-11: Conceptual Illustration of Engineering Durability

To have a good understanding of the durability of materials, the following needs to be considered (CSIR, 2015):

1. Mineralogical composition of the aggregate
2. Stage of weathering of the material
3. Secondary weathering of the material
4. The expected or local weathering process

Understandably, aggregates have a major influence on the durability of unbound and bound materials, as they consist of at least 80 percent, by mass of aggregate (Xuan, 2012). The durability of the aggregate shows the ability for it to maintain its original properties during the service life. These properties include grading, aggregate shape and physio-mechanical properties (CSIR, 2015).

Furthermore, aggregate degradation of weathered material will result in poor durability. Degradation can be divided into two categories which are disintegration and decomposition. Disintegration can occur while the pavement is in service or during construction of the pavement. In the latter case, loading induced by construction equipment causes deflection. Whereas, during the service life, when the stresses in the pavement exceed the tensile stresses, the material will disintegrate. This development causes a change in particle size distribution which affects the material grading and results in an increase in material fines as well as an increase in relative surface area of the material.

The other type of material degradation, referred to as decomposition, is a consequence of chemical changes to the aggregate. Chemical changes release secondary minerals which can have an influence on the Plasticity Index (PI) of the material. An increase PI will cause the shear strength of the aggregate to decrease (Paige-Green, 2015).

The durability issues discussed are relevant to both unbound and bound material, however, the latter are further associated with additional durability issues caused by the addition of stabiliser. The properties of bound materials, such as strength, are expected to increase over a certain period of time and be able to maintain this state for the duration of the design pavement life. This becomes challenging as the durability of bound materials are affected by external factors, such as environmental conditions and traffic loading, as well as internal chemical reactions.

The rate of degradation of bound materials is controlled by the rate at which moisture and gases penetrate the material. Penetrability can be described by considering the different transport mechanisms through material.

These transport mechanisms can be categorised by three phases:

1. Pressure-induced flow
2. Diffusion
3. Absorption

In general it is acceptable to understand the durability of a material as the ability of the material to resist the effects of moisture. And a major durability issue associated with, specifically bound, materials is carbonation. However, as stated by Netterberg & de Beer (2013), even in the case of a bound material exhibiting carbonation, the strength of the carbonated material may still be adequate for its use and purpose in the pavement.

For the scope of this research report it is important to understand how the properties of RCA contribute to the durability of its use as a pavement material and if it is necessary to consider additional durability concerns related to the use of RCA to those outlined above, in terms of bound and unbound materials.

2.5 Recycled Concrete Aggregate

Replacing Natural Aggregates (NA) with RCA has an indisputable positive environmental impact. By conserving NA's, the environmental is preserved as the need for new mining sites diminishes.

Specifications of Recycled Concrete Aggregate (RCA) as a pavement material are still being developed in South Africa as further understanding of the behaviour of this material is necessary. RCA is produced by crushing and sorting Crushed Demolition Waste (CDW). CDW is generated during the course of various construction and demolition processes, resulting in significant material variability, subject to the original source of the material. CDW can be classified, depending on the nature of the works, into categories such as roadwork material, excavated soil, demolition waste, site clearance waste, and renovation waste.

With an increased interest in RCA as a pavement material, greater interest has been shown in exploring novel and effective mechanical and/or chemical stabilization techniques to treat CDW before producing RCA (Jitsangiam *et al.*, 2014).

Table 2-4: Specific Gravity and Absorption of Recycled Aggregate (RA) and Natural Aggregate (NA) Reported by Different Researchers, Adapted from Verian et al. (2013)

Author	Specific gravity (coarse aggregate)		Absorption (%)	
	Recycled aggreagate	Natural aggregate	Recycled aggreagate	Natural aggregate
ACPA 2009	2.1-2.4	2.4-2.9	3.7-8.7	0.8-3.7
Gomez-Soberon 2002 (surface dry)	2.35-2.42	2.59-2.67	5.83-8.16	0.88-1.49
Gomez-Soberon 2002 (dry)	2.17-2.28	2.57-2.64	-	-
Poon et. Al 2004	2.33-2.37	2.62	6.28-7.56	1.24-1.25
Ann et al. 2008	2.48	2.63	4.25	0.73
Xiao et al. 2005	2.52	2.82	9.25	0.4
Abbas et al. 2009	2.42-2.5	2.71-2.74	3.3-5.4	0.54-0.89
Kou et al. 2007	2.49-2.57	2.62	3.52-4.26	1.11-1.12
Olorunsongo et al. 2002	2.6	2.61	-	-

2.6 RCA as a Pavement Material

Major critical problems with RCA as granular material in structural unbound layers:

- Sulphur compounds
- Fragmentation resistance
- Amount of attached mortar

Factors contributing to distress in both rigid and flexible pavements due to poor performance of unbound layers:

- Shear Strength
- Density
- Gradation
- Fines Content
- Moisture Level
- Particle Angularity and surface texture
- Degradation during construction
- Drainability

Problem factors in RCA properties to affect pavement performance:

- Shear strength
- Frost susceptibility
- Durability
- Stiffness

Most RCA material properties can be characterised and understood within a relatively short time, however, the long-term performance of RCA still needs a great deal of research. This can be understood as the durability of RCA as a material and with the presence of latent cement, carbonation is a notable durability issue.

Pertaining the research, when considering RCA as a pavement material, the question arises of whether carbonation is an issue of concern. It is well documented that the use of Recycled Aggregate (RA) in concrete (RAC) has potentially detrimental effects on the durability-related performance, more so than Natural Aggregate Concrete (NAC). Consensus on various literature studies of RAC is that an increased replacement level of NA with RCA leads to increased carbonation depth (Silva *et al.*, 2015). Cartuxo *et al.*, (2014) studied RAC containing the same content of Fine RCA (FRCA) and various types of water reducing admixtures exhibited up to 6 times greater carbonation depths than NAC. The performance of RAC was investigated by Amorim, de Brito and Evangelista, (2012)which focused on the influence of curing conditions on the durability aspects. This study found that 100% replacement of NA with Coarse RCA (CRCA) increased carbonation depths up to 49% and 31% at 28 and 91 days, respectively, after casting. A similar consequence was found by Evangelista and de Brito (2010)where 100% replacement by FRCA resulted in carbonation depths of 1.7 times greater. These differences can be related to the fact that greater Water Absorption (WA) properties are usually indicated by FRCA than CRCA, leading to greater permeability of RAC (Silva *et al.*, 2015).

Other than the percentage replacement, the quality and size of RCA influences the resistance to carbonation of RAC. Katz (2003), found that RCA exhibited similar physical properties such as latent cement content and WA, regardless of crushing age, thus producing similar carbonation depths in RAC. This finding was confirmed by Ryu (2002) who observed similar carbonation depths in RAC produced with RCA which exhibited varying WA values however the RCA was sourced from concretes with different strengths and latent cement contents. Nevertheless, as mentioned, the WA properties of RCA has a direct effect on the permeability of the produced RAC and Xiao, et. al (2012)showed that an increase in WA resulted in a decrease in the RAC's resistance to carbonation.

It is clear due to these factors that carbonation is an issue when using RCA and a higher degree of carbonation can be expected when RCA replaces the use of NA in concrete. However, the significance of this matter when RCA is used as a pavement material and the effect on the pavement life is not yet well understood. As poor durability of bound granular materials is already thoughtfully attributed to carbonation, theoretically this durability issue is expected to occur when cement products are present, as is the case of RCA. However, pure RCA (to which no cement has been added) contains latent cement particles adhered to the aggregate and its composition can be different to that of fresh stabiliser. So in this state, should the same durability issues, as that of bound pavement materials, be of a concern for materials containing RCA without the addition of cement. To gain insight into the severity of this potential

issue of using RCA, the hardening-process of the adhered latent cement, commonly referred to as self-cementation, of RCA material is considered. The degree to which RCA as a pavement material will self-cement is dependent on the presence of non-activated cement particles as well as the associated carbonation kinetics (Sun, 2010).

2.7 Self-Cementation of RCA

2.7.1 Introduction

One of the main challenges with using RCA as a pavement material is considering the self-cementation properties of this material. The adhered latent cement content of RCA consists of particles which are active and will readily react with water to form cementitious products, thus leading to an increase in stiffness of the material. The long-term development of stiffness in a pavement layer is beneficial providing that shrinkage and cracking is contained.

The active fractions of latent cement are exacerbated during the crushing procedure when producing RCA. The crushing of concrete and/or RCA (secondary crushing) further exposes active cement fractions and provides additional Interfacial Transition Zone's (ITZs). The ITZ represents the bond between the aggregate and cement. In terms of RCA, the ITZ will further represent the bond between the original aggregate and latent cement and the aggregate and new cement. The self –cementation of RCA occurs in the material when no cement is added and is thus further complicated by the addition of cement. When water is added to RCA to produce the required material, the hydration process is of particular interest as it initiates the chemical reaction of hydration. Furthermore, high WA properties of RCA weakens the ITZ as it causes a lack of water in the paste, impairing the hydration of cement. This weak ITZ constitutes a preferred path for CO_2 diffusion, which encourages carbonation (Silva *et al.*, 2015).

This section will develop an understanding of self-cementation by introducing the fundamentals of the hydration process, this is required to initiate self-cementation. Following this, typical test results that relay the stiffness performance of a material in terms of permanent deformation (PD) and M_r will be discussed.

2.7.2 Hydration Process of Portland Cements

The reaction of cement with water produces a paste of larger surface area than the plain cement powder, this paste hardens and acts as a glue between aggregates in bound pavement materials. The hydration process of Portland cements is complex as their typical compositions vary and will produce different chemical reactions when exposed to water. Table 2-5 provides a summary of the typical compositions of Portland cement.

Table 2-5: Typical Compound Compositions of Portland Cement (ACI, 2001)

Cement Type	Performance	C_3S	C_2S	C_3A	C_4AF	Fineness, m^2/kg
I	General purpose	55	19	10	7	370
II	Moderate sulfate resistance	51	24	6	11	370
III	High early strength	56	19	10	7	540
IV	Low heat of hydration	28	49	4	12	380
V	Sulfate-resistant	38	43	4	9	380

The main hydration reactions are summarised by the following expressions (Sun, 2010).

$$C_3S + (3 - x + y)H \rightarrow C_xSH_y + (3 - x)CH \quad (2\text{-}1)$$

$$C_2S + (2 - x + y)H \rightarrow C_xSH_y + (2 - x)CH \quad (2\text{-}2)$$

$$C_3A + 3C\bar{S}H_2 + 26H \rightarrow C_6A\overline{S_3}H_{32} \quad (2\text{-}3)$$

$$C_3A + C_6A\overline{S_3}H_{32} + 4H \rightarrow 3C_4A\bar{S}H_{12} \quad (2\text{-}4)$$

$$C_4AF + 2CH + 10H \rightarrow C_6AFH_{12} \quad (2\text{-}5)$$

Considering the equations represented above, it is clear that there are many combinations of each reactant that will contribute to hydration. Furthermore, each of the cement constituents play a unique role in the hydration process. The major crystallographic phases are:

C_3S - Tricalcium Silicate (also known as Alite)

C_2S - Dicalcium Silicate (also known as Belite)

C_3A - Tricalcium Aluminate

C_4AF - Tetracalcium Aluminoferrite (also known as Ferrite)

CSH_2 - Gypsum

It is important to note here that the above definitions are in accordance with cement chemistry notation, where:

C = CaO and S = SiO_2

Furthermore, gypsum is an important chemical composition of cement as it is added to prevent what is known as false setting, i.e. to prevent C_3A from instantaneously reacting with water. An increase in gypsum can lead to early silicate reactions.

The hydration reaction is exothermic and the heat generated creates the possibility of cracking caused by thermally induced stresses. The hydration of Alite produces lime and CSH as shown in equation(2-1). This reaction contributes to a large portion of the strength of cement as the CSH compound consists of short fibre structures.

Belite, too, reacts to form CSH (equation(2-2)), which contributes somewhat to the strength of the cement however it is not as influential as Alite. The reason for this is that the reaction proceeds at a slow rate and the initial contribution to strength is very slow. However, this reaction continues indefinitely and therefore contributes to the long term strength development of cement.

Equations (2-3) and (2-4) represent two possible reactions for the hydration of C_3A. The former reaction takes place at a very slow rate, whereas, the latter, reacts rapidly and requires the addition of Gypsum. Gypsum prevents flash setting of the cement paste, a reaction which leads to immediate strengthening of the paste within minutes of mixing. These two equations supplement one another in the hydration process of cement. Lastly, the hydration of ferrite is significantly slow.

It is also worth mentioning that carbonation can accelerate the hydration process of cement by converting Alite and Belite into $CaCO_3$ and CSH (Sun, 2010). Carbonation will be discussed in further detail at a later stage.

2.7.3 Self-cementing Behaviour

Performance base tests have shown a positive growth in M_r of crushed concrete and a decrease in stress dependency (Arm, 2001) in both laboratory and field conditions. The results shown in Figure 2-12 depict almost no influence of time on the change in M_r for granite. However, in the case of the crushed concrete (RCA), there is a clear increase in M_r from 1 day to 60days. This can be attributed to the self-cementation of RCA.

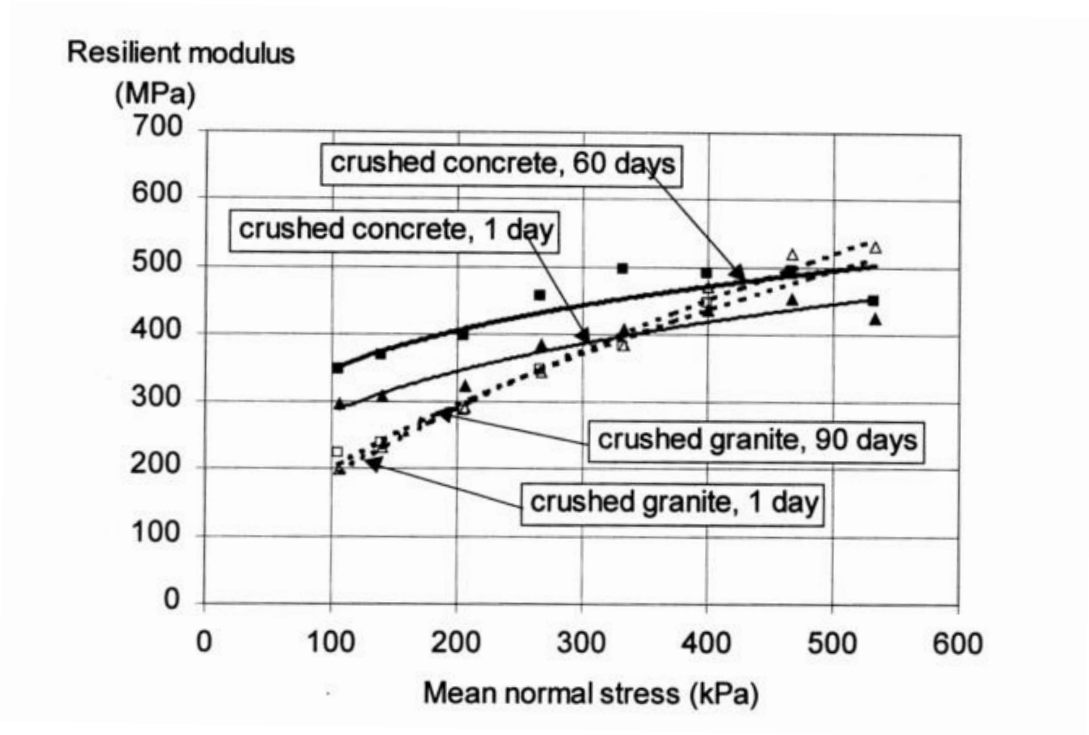


Figure 2-12: Comparison of Change in Resilient Modulus from Repeated Load Triaxial Tests on Granite and Concrete (Arm, 2001)

The most encapsulating results to support the self-cementing behaviour of RCA is perhaps that of van Niekerk, (2002). He showed that the stress dependency of M_r and poisson (ν) was directly influenced by the applied stress regimes. Two types of testing regimes were performed, which he refers to as 'mild' and 'severe' at increasing confinement pressures (12-72kPa). These tests were performed on granular materials that showed no self-cementing (SC_N) and on granular materials which did (SC). In the case of the granular material without cementing, the M_r increased with increasing confinement stress. He concluded that damaging bonds of the granular material with cementing properties, resulted in a greater effect on ν than on M_r when a more severe testing regime was implemented. Furthermore, his work concluded that curing was considered to be the lowest influencing variable, however, curing times were limited. Notably, he characterised the behaviour of RCA as being similar to a weakly cemented material(Van Niekerk, 2002).

According to Paige-Green (2010), FRCA is more susceptible to hydration due to the particles containing a higher surface area which will more readily react to water. This leads to an increased stiffness and strength. He also acknowledged that RCA had the potential to form secondary cementation which is caused by the latent active cement particles.

In conclusion, RCA as a pavement material has potential added benefits of self-cementation. However, as with bound materials, cementation can be detrimental to pavement layers if these properties are not designed for accordingly.

2.8 The Carbonation Phenomenon

2.8.1 Introduction

Carbonation is an inevitable environmental process in time. The atmosphere provides the major source of CO_2 gas with an average concentration of 3500 ppm. Ominously, this concentration increases to 10 000-50 000 ppm by volume in deeper soil layers, attributed to the degradation organic matter (Lagerblad, 2005). Under the influence of prolonged exposure to CO_2, cementitious materials experience physical and chemical transformations. These changes pose durability issues for cementitious materials as typical changes include a reduction in both alkalinity (pH) and porosity.

In the early 1980s numerous cases of disintegration and failure of stabilized pavement layers, were reported in South Africa. Netterberg and Paige-Green (1984) affiliated the carbonation phenomenon as the possible cause of deterioration of stabilized pavement layers. This concern would later be confirmed and carbonation is now seen as a major durability issue of stabilized materials. While Netterberg and Paige-Green (1984) emphasised the influence which careless construction methods (specifically poor and/or insufficient curing) could have on the effect of the stabilizer, this was later countered by Botha et al. (2005). After in-depth research based on a number of problem projects, Botha et al. (2005) identified the carbonation of stabilized pavement layers as a water driven reaction within the material. This claim is supported as it is known that the carbonation reaction takes place in the pore water system of the material (Engelsen *et al.*, 2005). However, it will be shown that only the right amount of water, under specific conditions will drive this reaction and too much or too little water could abrupt the reaction. It is further reasoned that activities within the material itself is out of the hands of a contractor and if anything, it is the responsibility of the consultant to understand the material and design accordingly.

In theory, the carbonation process appears simple, however, in reality this is a complex multivariate phenomenon. There are several parallel chemical reactions occurring at varying times as well as a number of external and internal factors influencing the course of carbonation as shown in Figure 2-13.

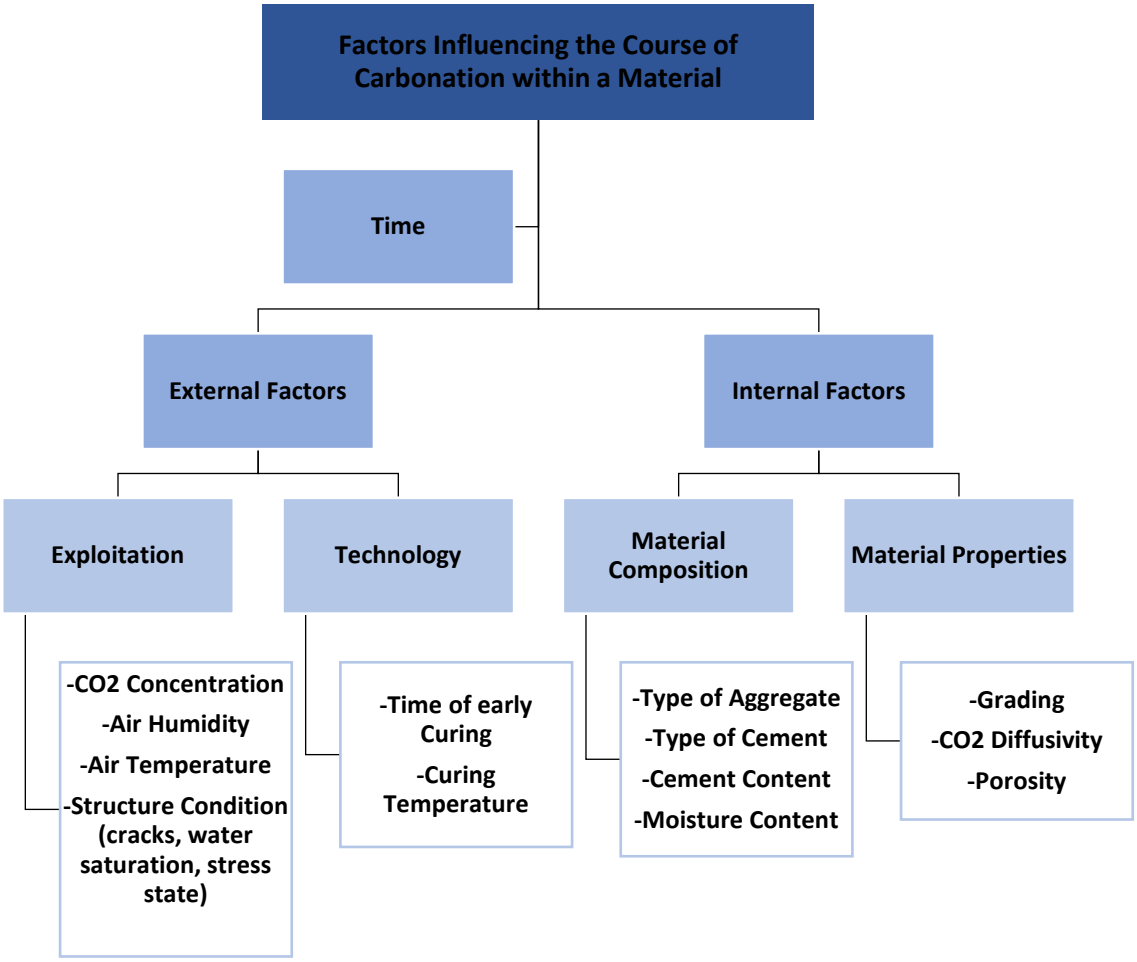


Figure 2-13: Classification of Factors Affecting the Course of Carbonation (Adapted from Czarnecki & Woyciechowski (2015))

A thorough comprehension of the carbonation phenomenon of cementitious materials may never be conquered due to the illustrated complex nature. Nevertheless, it is fundamental to account for the effect which it may have on cementitious pavement materials.

2.8.2 Chemistry of Carbonation

Carbonation of stabilised material is a natural occurrence which involves the reaction of atmospheric CO_2 gas and available calcium bearing phases of the stabilizer. This phenomena has had more studies in concrete than that of stabilised pavement materials in the form of experimental or analytical experiments (Rezagholilou and Nikraz, 2012).

These phases are most commonly introduced through the products of cement hydration (Sun, 2010). In cement chemistry, hydration refers to the reaction of hydraulic cement with water. This reaction is the cause of Portland cement hardening and strength development. In principle, the gas reverts the cementitious product back to its original state of limestone.

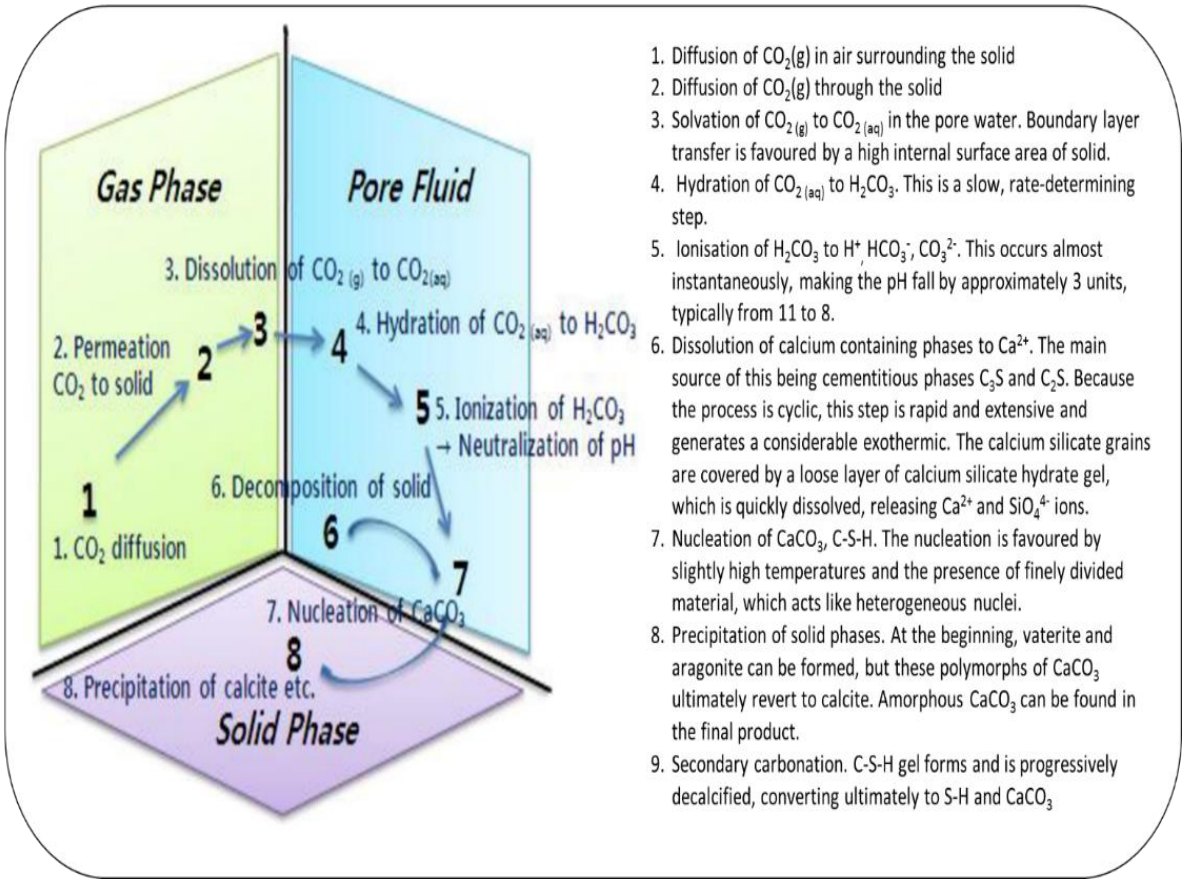


Figure 2-14: Schematic Illustration of the Accelerated Carbonation Process (Lim et al. 2010)

The carbonation reaction takes place in the aqueous phase within the pore structure of the material. It requires the dissolvation of atmospheric CO_2 into the pore water before it can react with available Calcium-bearing compounds to produce the $CaCO_3$ precipitate. Figure 2-14 depicts an illustration, adapted from *Lim et al. (2010)*, of the various phases of the accelerated carbonation phenomenon along with a brief description of each step, outlined by Fernández Bertos et al. (2004) and Sun, (2010).

This sequence will be discussed further in the following sections along with the applicable chemical reactions which are attributed to each step.

2.8.2.1 Phases of Carbonation

A general overview of the above mentioned carbonation phases is viewed, simply, as the formation of a solidified product ($CaCO_3$) which is the re-precipitation of the solvation of calcium ions (Ca^+). The solvation of Ca^+ is induced by the ionised CO_2. The main source of Ca^+ is the hydrate product, $Ca(OH)_2$ and the conversion of this compound is the principal carbonation reaction. Thus, the following explanations are based on the carbonation of $Ca(OH)_2$ specifically. Carbonation of other compounds is possible but, are negligible in the overall process. A brief discussion of other products will be given at the end of this section.

2.8.2.2 Gas Phase

Matter is considered to be in one of two states, fluid or solid. These 'states of matter' are recognised based on the response of the matter to an applied force. The first observable characteristics of a gas, include (Illston and Domone, 2001):

- Gases are of low mass density, expand to fill a container, are easily compressed and have low viscosity
- Gases exert a uniform pressure on the walls of their container.
- Gases diffuse readily into each other.

The first of these characteristics suggest that gas particles are not in direct contact with each other. When gases are moving in random directions in constant motion but high speeds, the second and third characteristics will be observed (Illston and Domone, 2001).

The gas phase of carbonation involves the diffusion of CO_2 gas into the material. Diffusion is instigated by the collision of numerous frenzied individual atoms or molecules. The rebound of these entities is random and unpredictable however, a steady and systematic flow can result from sufficient participants in such movements.

The diffusion of matter (gas or liquid) is governed by the relative pressure and concentration of all participants.

These variables influence the total flux, J, of particles through a plane. Fick's first law of diffusion is shown as:

$$J = \frac{-DdC}{dx} \tag{2-6}$$

Where,

J = Number of particles flowing in the x-direction per unit time per unit cross-sectional area [mol/m^{2}s]

D = Diffusion coefficient (proportional to the average distance travelled by a particle before colliding with another and the frequency of collisions) [m^2/s]

$$\frac{dC}{dx} = \text{Concentration gradient} \tag{2-7}$$

The above variables can be related to concrete (and in a similar way to pavement materials) by understanding J as the transport rate of CO_2 and carbonate ions through unit area with D relating to a material property which is dependent on permeability.

Fick's first law can be used to understand the amount of material that is altered by carbonation by understanding the speed of the phenomenon (Paige-Green, 2008). However, the depth of material which is altered by carbonation is better presented by Fick's second law of diffusion as it incorporates the surface of the material. Therefore, in the non-steady state, where concentration changes in both space and time, Fick's second law can be applied and is expressed as:

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial^2 x} \tag{2-8}$$

Where,

∂t is a time factor, c is concentration and x is surface area.

Solving this equation is challenging as the inward diffusion of CO_2, Carbonate ions (CO_3^-) and outward diffusion of Calcium ions (Ca^{2+}) must be considered simultaneously. Together with this, the connective porosity must be considered and how solubility and precipitation will affect this. Bary & Sellier (2004) used a mass balance approach in an attempt to solve this coupled diffusion equation and produced a model in which they assumes that the remaining CSH in has a CaO/SiO_2 ratio of 0.85 and 1.65 in the fully carbonated zone and uncarbonated zone, respectively.

2.8.2.3 Pore Fluid Phase

Liquids exhibit mostly the same properties as those of gas. With low viscosities (although some orders of magnitude higher than those of gases), liquids flow irreversible under small forces and most diffuse readily into each other (Illston and Domone, 2001).The main difference between the solid state and gas state of matter is that the particles of the former are in contact but are free to move relative to each other. Furthermore, the vapour-liquid transition is derived from the perfect gas law:

$$PV = nRT \tag{2-9}$$

Where,

P = Pressure [kPa]

V = Volume [m3]

R = Gas constant [mol/K]

K = Temperature [K]

Van der Waals adapted this equation to include two important factors; the volume of the particles themselves and the forces of attraction between these particles (Illston and Domone, 2001). The van der Waals equation is:

$$\left(P + \frac{a}{V^2}\right)(V - b) = RT \qquad (2\text{-}10)$$

Following the dissolution of CO_2 into the pore water, a weak carbonic acid is formed which dissociates into hydrogen and carbonate ions. Figure 2-15 illustrates this mechanism of carbonation (Czarnecki and Woyciechowski, 2015).

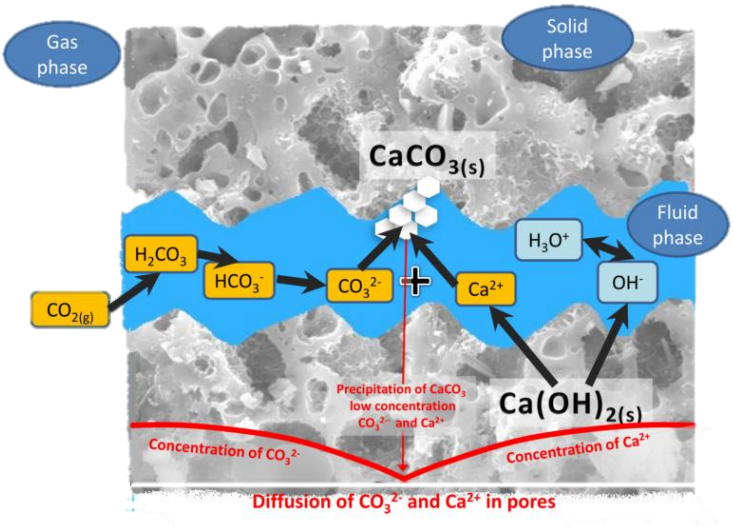


Figure 2-15: Mechanism of Carbonation (Czarnecki and Woyciechowski, 2015)

Thiery and Dangla et al. (2013) propose that the chemical reactions occurring during carbonation are not instantaneous with respect to CO2 diffusion through the porous network. Specific chemical and physical properties are required for a material to be carbonated. The carbonation of cementitious material is commonly expressed with the following equation:

$$Ca(OH)_2 + CO_2 \xrightarrow{H_2O} CaCO_3 + H_2O \qquad (2\text{-}11)$$

However, this is purely a simplification of various microscopic chemical reactions which occur simultaneously at varying rates dependant on factors such as relative humidity, partial pressure of CO_2.

As previously mentioned and now supported by the equation above, it is necessary for CO_2 to be dissolved in water to form the bicarbonate (HCO_3^-) or carbonate (CO_3^{2-}) ion. This process is outlined below along with the associated pH value of each reaction:

$$CO_2(g) + H_2O = H_2CO_3 \quad (2\text{-}12)$$

$$CO_3 = HCO_3^{2-} + H^+ \quad ; \quad pK_a = 6.35 \quad (2\text{-}13)$$

$$HCO_3^{2-} = CO_3^{2-} + H^+ \; ; \quad pK_a = 10.332 \quad (2\text{-}14)$$

The formation of these ions are dependent on the pH of the water. Characteristically, in concrete, the carbonated zone (low pH) will mainly consist of HCO_3^{2-} whereas CO_3^{2-} will be predominant in the un-carbonated zone (high pH) of the cement paste, the same assumption can be made for stabilised materials (Lagerblad, 2005). In the latter case, the pore water is often saturated with calcium hydroxide Ca $(OH)_2$ which is dissolved in the pore water to form Calcium (Ca^{2+}) and Hydroxide (OH^-) ions.

2.8.2.4 Solid Phase

The presence of calcium ions (Ca^{2+}) is necessary for the formation of the $CaCO_3$ precipitate. Various hydration products are capable of releasing Ca^{2+}, however, the principal source of these ions in hydrated Portland cement is $Ca(OH)_2$ (Sun, 2010). The carbonate ion will react with Ca^{2+} in the pore solution resulting in lower concentrations of Ca^{2+} as it is consumed. This encourages the dissolution of primary calcium hydroxide (CH) and is supported by applying Le Chatelier's Principle, which states:

'When any system at equilibrium is subjected to change in concentration, temperature, volume or pressure, then the system readjusts itself to (partially) counteract the effect of the applied change and a new equilibrium is established'.

The reaction is expressed as follows:

$$CaOH(s) \overset{H_2O}{\Longleftrightarrow} Ca^{2+}(aq) + OH^-(aq) \quad (2\text{-}15)$$

$$Ca^{2+}(aq) + CO_3^{2-}(aq) = CaCO_3(s) \quad (2\text{-}16)$$

It is also worthy to note that the solubility of $CaCO_3$ (9.95×10^{-4}) is much higher than that of $Ca(OH)_2$ (0.99×10^{-8}). Thus, $Ca(OH)_2$ will dissolve and $CaCO_3$ will precipitate, this process will continue until a point when $Ca(OH)_2$ is fully consumed (Lagerblad, 2005).

2.8.2.5 Additional Cementitious Products

CO_2 attacks $Ca(OH)_2$ first and will proceed to attack other cementitious compounds only when the pH is below 12.4, notably this is the value for a saturated calcium hydroxide solution. Other constituents susceptible to carbonation include the hydrate products, CSH and

ettringite/monosulphate (AFt/AFm). The consumption of the latter is related to the pH under non-equilibrium conditions (Lagerblad, 2005). AFm will decompose into AFt and aluminate compounds at a pH of 11.6. Further reduction of pH to around 10.6 will see the decomposition of AFt resulting in sulphate ions and aluminium hydroxide compounds. Carbonation of the products of these reactions is possible but will not be discussed further.

At pH values of less than 9.2, all of the original Ca-phases will be absent. The hydrate products, are in equilibrium with and stabilised by high pH and Ca^{+} in the pore solution. Typically a pH of 12.4 is needed to ensure stabilisation of the hydrate products and allow for the reactions to progress (Gourley and Greening, 1999). Thus, a decrease in pH and Ca^{+} indicates the consumption of CH which will encourage the congruent dissolution of CSH. Carbonation effectively depletes the calcium content of CSH and this changes the composition of CSH, as well as result in a lower Ca/Si ratio. This ratio is thought to be 0.85 and 1.65 in the fully carbonated and uncarbonated zones, respectively (Lagerblad, 2005). A simple explanation of this is that during the chemical reaction of CSH, CH is released which is then carbonated to form a lower content of CSH.

This explanation is expressed below followed by the carbonation of CSH:

$$CSH_1 = CSH_2 + CH, where\ Ca/Si_1 > Ca/Si_2 \quad (2\text{-}17)$$

$$(3CaCO \cdot 2SiO_2 \cdot 3H_2O) + 3CO_2 \rightarrow (3CaCO_3 \cdot 2SiO_2 \cdot 3H_2O) \quad (2\text{-}18)$$

This equation represents the most complicated transformation as it is composed of short silica chains bound together by Ca^{+} and OH^{-} ions.

The carbonation of un-hydrated products, Alite (C_2S) and Belite (C_3S) is expressed with the following equations, respectively:

$$(2CaO \cdot SiO_2) + 2CO_2 + nH_2O \rightarrow (SiO_2 \cdot nH_2O) + 2CaCO_3 \quad (2\text{-}19)$$

$$(3CaO \cdot SiO_2) + 3CO_2 + nH_2O \rightarrow (SiO_2 \cdot nH_2O) + 3CaCO_3 \quad (2\text{-}20)$$

Where,

n = Positive number of moles of water that is conserved through reactions

Interestingly, the carbonation of the un-hydrated products do not directly affect the alkalinity of concrete. These reactions may be accounted for in a worst-case scenario, where enough water is available as well as all carbonatable constituents are available to CO_2 (Peter *et al.*, 2008).

2.9 Controlling Variables of Carbonation

The carbonation process is essentially dependent on the presence of CO_2 ions in the pore water and available Ca^{2+} ions with which it can react. Therefore the diffusivity and reactivity of the gas are the governing parameters of the carbonation reactions. These parameters depend on a number of influencing extrinsic and intrinsic factors as defined below (Fernández Bertos *et al.*, 2004):

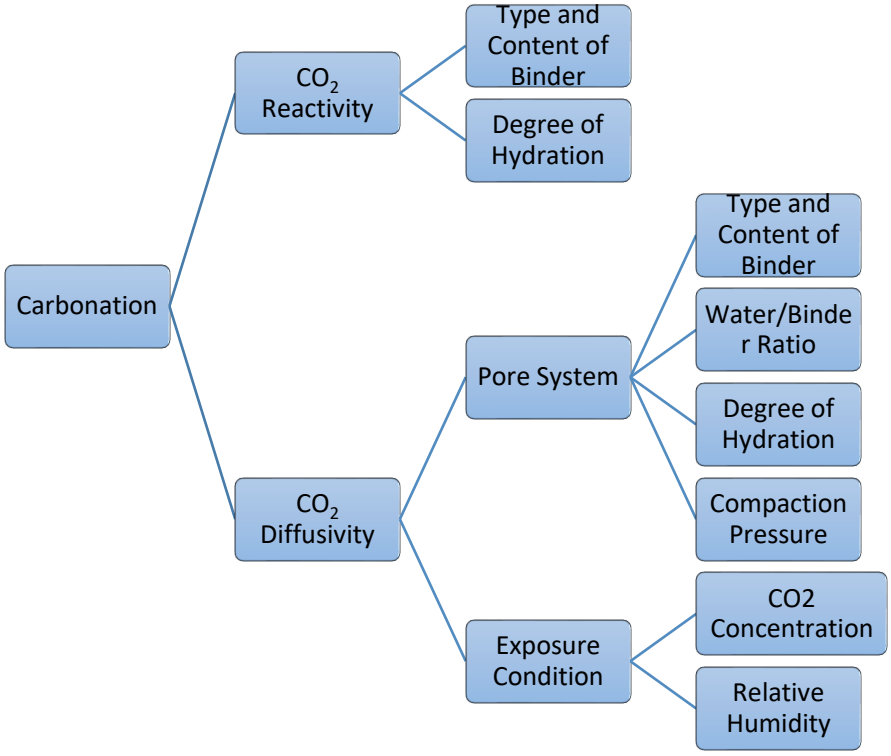


Figure 2-16: Illustration of the Governing Parameters of Carbonation (Adapted from Fernández Bertos et al. 2004)

2.9.1 Material Composition

The maximum carbonation will occur at a specific Relative Humidity (RH), a specific open porosity and specific cement type. Specific cementitious phases as well as the presence of certain metals in a material will influence the rate of carbonation as well as the production of $CaCO_3$. The amount of CO_2 consumed by a material has been related to the quantity of $Ca(OH)_2$ present in the hydrated cement paste, however, further studies show that CSH and Aluminate pastes have the potential to carbonate as well. Fernández Bertos et al. (2004) reported the use of the Steinour formula to calculate the theoretical maximum CO_2 uptake capacity due to carbonation as a function of the chemical composition of the original material. This equation is expressed as:

$$CO_2(\%) = 0.785(Ca) - 0.7SO_3) + 1.09Na_2O + 0.93K_2O \qquad (2\text{-}21)$$

Similarly, Sun (2010), refers to Huntinger's formula:

$$CO_2(\%) = 0.785(CaO - 0.56CaCO_3 - 0.7SO_3) + 1.091M_gO + 0.71Na_2O + 0.468K_2O \quad (2\text{-}22)$$

This formula assumes that all the magnesium Oxide (MgO), Sodium Oxide (Na_2O), Potassium Oxide (K_2O) and all the Calcium Oxide (CaO) in the cement, excluding that in the Calcium Carbonate ($CaCO_3$) and Calcium Sulphate ($CaSO_4$), are available to react with CO_2 to form carbonates.

Water content refers to the amount of free water existing in the pores of the solid matrix (Sun, 2010). The carbonation reaction takes place in the aqueous phase i.e. within the pore water itself. However, a very dry material does not carbonate as the lack of water prohibits the formation of ions and subsequently the reaction to form $CaCO_3$. In contrast, too much water present in the pore system will limit the carbonation reaction and the formation of $CaCO_3$ will be very slow. In summary, pore water plays a vital role in the carbonation reaction as it is the driving force behind the salvation and hydration on CO_2. Without the presence of water in the pore system, the Ca^{2+} ions are unable to dissolve from the solid and cannot react with the aqueous phase of CO_2.

Besides the importance of water being present, access to this water is also fundamental in encouraging carbonation. This is restricted by the geometry of the capillary system which can be presented better by the porosity and permeability of a material. During carbonation, the calcium phases present in cement are susceptible to reacting with CO_2 to form $CaCO_3$ precipitate. This precipitate can deposit itself within the capillary system which changes the permeability of the material and ultimately, the porosity is altered (Song and Kwon, 2007). In effect, the microstructure of the material is continuously changing during the carbonation process.

The porosity and permeability of stabilised materials is directly related to the compaction pressure during the construction of the material layer. When compaction pressure is increased, the porosity and permeability of the material is increased which increases the development of material strength. On the other hand, low material porosity hinders the diffusion of CO_2 into the material resulting in lower production of $CaCO_3$ and consequently a decrease in strength development.

2.9.2 Exposure Conditions

Taking into account the reactions needed for carbonation to occur, it is evident that the environmental conditions play a vital role in this phenomenon. In the first phase of carbonation, where gas diffusion is initiated, the concentration of CO_2, RH and temperature are the main variables influencing the carbonation reaction.

2.9.2.1 Temperature

It is well known that temperature has a direct influence on chemical reactions. An increase in temperature provides increased energy for a reaction, thus, the diffusivity of CO_2 is increased and carbonation is encouraged. However, solubility of the compounds required for the carbonation reaction, such as CO_2 and $Ca(OH)_2$ decrease with increasing temperature. For this reason, the carbonation rate has the potential to decrease at increased temperatures. The pH of lime at 25°C is usually 12.4, however, pH is known to vary considerably with temperature (CSIR, 2015). This occurrence is a reflection of the effect which temperature has on the cementation process. This process provides the products necessary for the carbonation process and thus, temperature will influence carbonation.

2.9.2.2 CO_2 Concentration

A higher amount of CO_2 concentration in the gas phase, will relate to a higher rate of carbonation (Fernández Bertos *et al.*, 2004). The cement products present in a material and their reaction to CO_2 predominantly affects the magnitude and depth of carbonation. Additional to the concentration of CO_2, the partial pressure of CO_2 (PP_{CO2}) influences the CO_2 diffusion rate in the carbonated zone. A low PP_{CO2} in the atmosphere (±0.03%) is attributed to the slow and inconsistent development of the strength of cement products. Fernández Bertos et al. (2004) suggested that by varying the PP_{CO2}, the rate of carbonation of cement paste can be controlled and so can the compressive strength. Hyvert et al. (2010), used X-ray diffraction to show that apart from CH, AFt and aluminates were carbonated efficiently at low PP_{CO2} while Šavija & Luković (2016) cited that the carbonation rate of CSH increased with increasing PP_{CO2}.

Coupled with the PP_{CO2}, the gradient thereof has been proven to have a significant effect on the degree of carbonation. A basic understanding of this is represented as a cyclic CO_2 exposure, where the influx of CO_2 is stopped periodically and then again resumed after a resting period. Many accelerated lab carbonation setups incorporate this as it prevents saturation due to the formation of H_2O during the carbonation reaction and re-establishes gaseous CO_2 pathways (Šavija and Luković, 2016). Figure 2-17 illustrates the difference in continuous carbonation and cyclic carbonation with the latter depicting parts of the small pores

being emptied during the drying cycle. The continuous carbonation shows these small pores being filled with water which is released as the carbonation reaction proceeds.

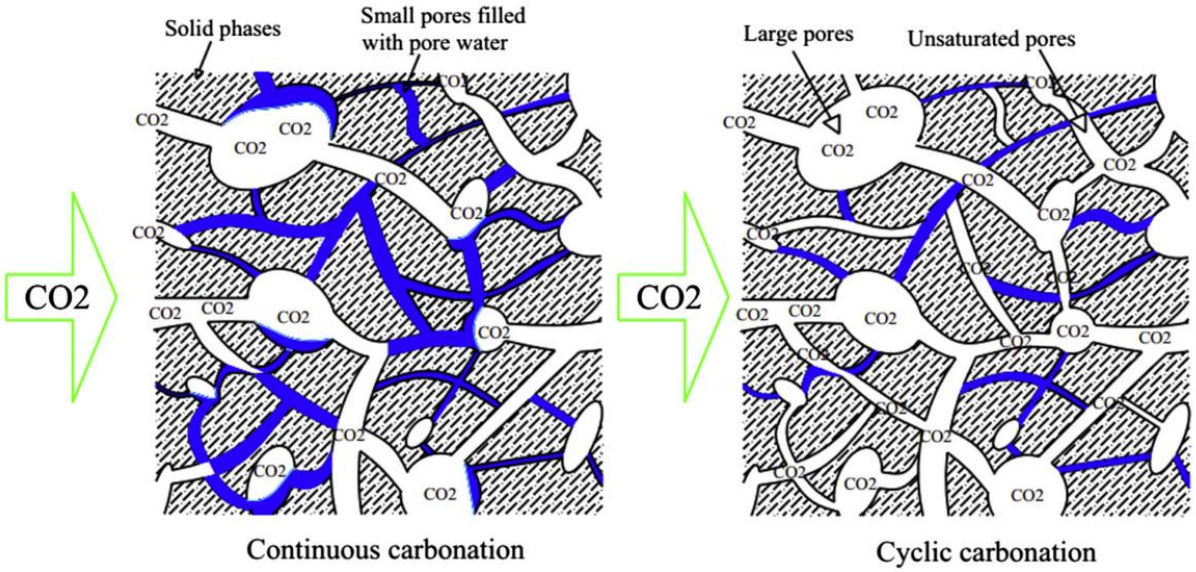


Figure 2-17: Conceptual Illustration of the Comparison between Continuous and Cyclic Carbonation of a Cement Paste (Šavija and Luković, 2016)

In a pavement layer, the PP_{CO2} will increase as a result of the degradation of organic matter (Lagerblad, 2005) and this variable is therefore important to consider when understanding the kinetics of carbonation.

2.9.2.3 Relative Humidity

Relative Humidity (RH) is the ratio of two pressures:

$$RH(\%) = \frac{p}{p_s} x100 \qquad (2\text{-}23)$$

Where p is the actual partial pressure of the water vapour present in the ambient and p_s the saturation pressure of water at the temperature of the ambient.

The literature presented thus far leads to a consensus on the importance of the availability of moisture (or lack thereof) in governing the rate of the carbonation procedure. RH is considered as a controlling variable of the coupled diffusion mechanism of carbonation as it is often used to express the moisture content of an environment or within a material. The effect of RH on carbonation depth for different grades of concrete was reported by Roy et al. (1999) at measurement periods of 1, 4, 8, and 16 weeks. The results, shown in Figure 2-18, found that the same general trend is observed for various concrete grades and there is an optimal RH level at which the carbonation depth is optimum. The RH in the range of 50-75% and 85-90% was accompanied by a significant increase in carbonation depth.

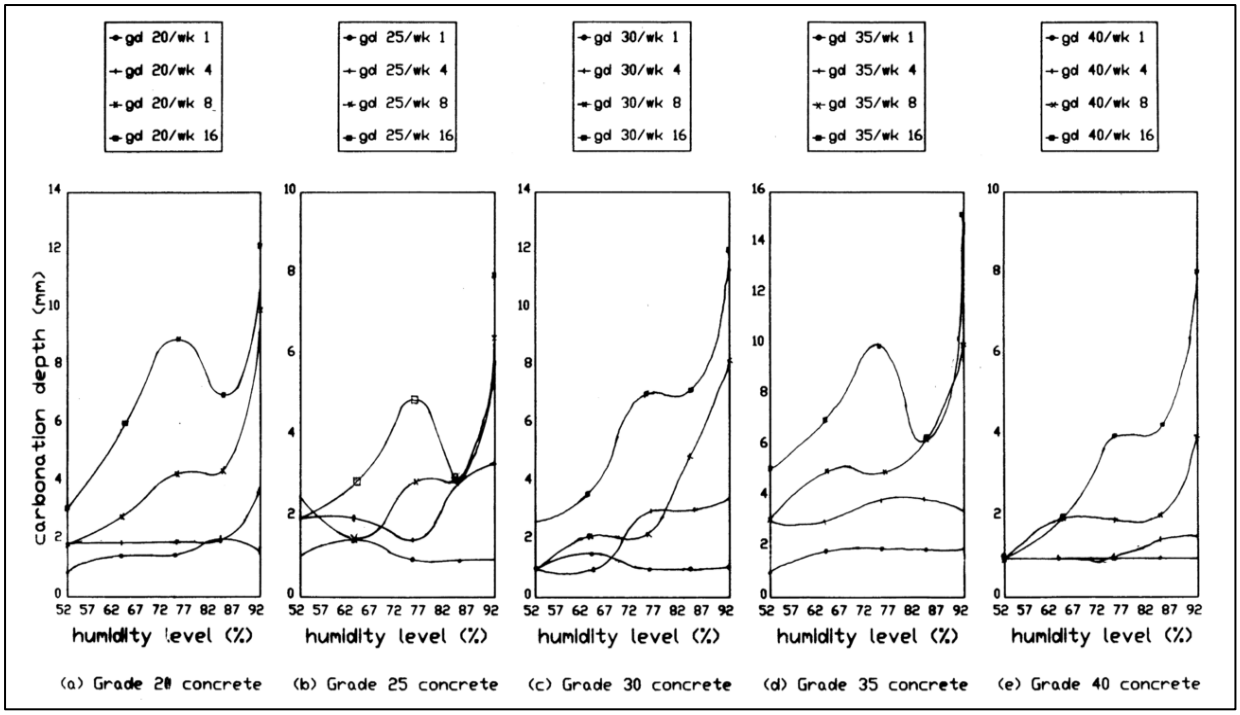


Figure 2-18: Carbonation depth vs Humidity for Different Grades of Concrete (Roy, Poh and Northwood, 1999)

This range is attributed to the two conflicting processes of carbonation, first the diffusion of CO_2 and second the reaction kinetics, which necessitate a compromise in the required RH. In general, a range of 55-65% is reported as the optimum RH needed for carbonation to proceed.

Xuan (2012) considered the influence of curing conditions on the reduction in UCS of cement treated recycled crushed concrete and masonry aggregates for pavements. He found that when the RH of the specimen was 50%, the reduction in UCS ranged from 10 – 20%. The reduction in UCS was almost twice as high (20 – 35%) at 100% RH. Field measurements of RH in the base layer of a pavement structure are reported as well over 99% which varies during daily changes in temperature (Netterberg and de Beer, 2013).

Rossick (2014), cited that carbonation almost only occurs in concrete pores when RH is between 40% and 90%. Furthermore, she adds that when the RH in the pores exceeds 90%, the diffusion of CO_2 into the pores is inefficient. Whereas, at low RH (<40%), CO_2 is unable to dissolve in the pore water.

2.10 Influence of Carbonation on Pavement Materials

Since CO_2 can react with the hydration products of the cementation process, it is possible that this would counteract the benefits of chemically stabilised pavement materials (Gourley and

Greening, 1999). Theoretically, this will result in increased plasticity and decreased material strength. The presence of organic material will aggravate the reaction as their decomposition increase the CO_2 concentration in soil to levels much higher than those found in the atmosphere. As the concentration of CO_2 exacerbates the potential for carbonation,

The products of carbonation induce important physical and chemical changes. (Morandeau, Thiery and Dangla, 2014) mentions several studies which have observed reduction in porosity after carbonation both on site as well as under accelerated exposure conditions and concludes that as a result, the material strength is increased.

2.10.1 Physical Consequences

Other than carbonation causing shrinkage and cracking of cementitious material, in addition, carbonation results in the deposition of $CaCO_3$ precipitate within the material pore structure. Therefore, as a result of the CO_2 binding with the available and favoured cementitious products, a change in density is observed. Together with the formation of the $CaCO_3$ precipitate, the expelling of moisture during the carbonation reaction blocks the pore structure. Rigo da Silva *et al.* (2002), found carbonation reduced the open porosity of concrete by 5-12%. As these changes take place on a microstructural level, the amount of small pores are decreased as a result of the blockage of pores. It appears that the fundamental influence on the structural properties, due to carbonation, is to decrease the pore volume, and ultimately the permeability, of the cementitious system.

The main reaction involves the carbonation of $Ca(OH)_2$ which is accompanied by an increase in solid volume. Based on specific gravity and the difference in molar volumes of $Ca(OH)_2$ and $CaCO_3$, an expected increase of 11.8% can occur in solid volume (Fernández Bertos *et al.*, 2004).

2.10.2 Chemical Consequences

The discussion of hydration of cement in this research study mentioned the fact that all of the products resulting from the hydration reactions, are prone to carbonation. The main reactions involved in the carbonation of these hydration products are the decalcification of $Ca(OH)_2$, CSH gel and AFt (González *et al.*, 2004). As discussed, the principal reaction of carbonation involves the reaction of CO_2 with dissolved $Ca(OH)_2$ to produce the $CaCO_3$ precipitate (refer to equation (2-11) within the pore structure.

Precipitation involves three main steps and with each of them come a chemical consequence. These precipitation steps are outlined and their subsequent chemical consequence cited (González *et al.*, 2004):

i. Dissolution of $Ca(OH)_2$

Initially, Ca^{2+} ions are abundant in the pore water of a material as a result of the dissolution of $Ca(OH)_2$. Carbonation lowers the concentration of $Ca(OH)_2$ and through decalcification of the CSH gel, more Ca^{2+} is provided. The kinetics of the dissolution of the $Ca(OH)_2$ is difficult to constitute as it is a by-product of the CSH gel which contains as highly variable stoichiometry. Meaning, that it can be formed through many different ratios of C, S and H constituents. Together with these processes, the dissolution of AFt, Alite and Belite, all have the potential to further provide Ca^{2+}.

ii. CO_2 Absorption in Pore Water and Formation of Carbonate Ions

The diffusion and solubility of CO_2 depends on a number of variables (as discussed previously) with the main ones being temperature, pressure and concentration. Once CO_2 has entered the material matrix and is absorbed, it hydrates rapidly in the pore water to produce bicarbonate and carbonate ions, respectively.

iii. Chemical Reaction and Precipitation

The principal carbonation reaction (equation (2-11) begins rapidly and slows down over time. $CaCO_3$ precipitate fills the pore space and increases the density of the cement paste. This filling of pores, has a direct relationship with mass transfer. The ingress of CO_2 and mitigation of Ca^{2+} are both hindered and at the same time, so is the egress of water.

In conclusion, the main chemical consequences as outlined above, lead to a change in the alkalinity of the pore water of the material. This is as a result of the formation of various ions.

2.11 Measuring Carbonation

Common methods used to detect the carbonation progress of bound materials, as well as cement and concrete, include (Sun, 2010):

- Thermogravimetry Analysis (TGA)
- X-Ray Diffraction (XRD)
- Scanning Electron Microscopy (SEM)
- Acid/Base Indicators

These methods are most useful in physically distinguishing the carbonated zones from the non-carbonated. These methods are considered to be destructive as it is necessary for the carbonation process to be interrupted in order for the testing to commence. TGA is a quantitative method and is able to measure the amount of $CaCO_3$ and $Ca(OH)_2$ in cement paste attached to RCA after carbonation (Zhang *et al.*, 2015). Furthermore, it presents the

changes which have taken place as a result of carbonation and can be used to indicate a carbonation depth-profile. A non-destructive alternative to this test method is gamma-ray attenuation which is able to identify density profiles in materials (Morandeau, Thiery and Dangla, 2014). XRD and SEM are measuring techniques used by researchers for material characterisation. On a micro-scale, microstructural changes can be characterised by these two methods.

In practice, the most widely used method is acid/base indicators. For ease of reporting and practicality, these indicators are the most simple of the methods to detect the presence of carbonated material. Spraying materials with phenolphthalein and dilute hydrochloric acid (HCL) can assist in indicating material has been carbonated (SAPEM, 2013). Phenolphthalein is a pH indicator which appears fuchsia-pink at pH>10 (uncarbonated material) and colourless when pH<8.3 (carbonated material). In addition to phenolphthalein, HCL is sprayed adjacent to the strip where phenolphthalein was sprayed (SAPEM, 2013). The combination of the outcome of these indicator tests is summarised in Table 2-6. This table indicates that where the phenolphthalein appears fuschia-pink and the dilute hydrochloric acid does not effervesce, the chance that carbonation has indeed occurred and there was no carbonate present in the original material to begin with.

Table 2-6: Determination of the Presence of Carbonation (Gourley and Greening, 1999)

Phenolphthalein	Dilute hydrochloric acid	Phenol red	Indication of carbonation	Carbonate in original material
Red	No Effervescence	-	None(1)	Absent
Clear	Effervescence	Red	Carbonated	Absent
Clear	No Effervescence	Red	No Stabiliser added(1)	Absent
Red	Effervescence	-	None	Present(3)
Clear	Effervescence	Red	Carbonated(2)	Present

Notes:
(1) Partial carbonation cannot be ruled out
(2) Cannot rule out that stabiliser was not added
(3) If carbonates not present some partial carbonation must have occurred

Morandeau, et. al (2014) identifies a drawback in using phenolphthalein as an indication of carbonation. This is related to the case where $CaCO_3$ is formed and surrounds the portlandite crystals. The phenolphthalein will not indicate the fuchsia-pink (or red) colour indicative of the presence of portlandite and will instead appear colourless.

The transition point indicated by the combined results of the indicators, is reported as the carbonation depth (x). Numerous studies have equated x to a combination of variables to model the depth of carbonation. The most common finding is that the depth of carbonation is

a function of the square root of time. These models can be very complex as the variables influencing carbonation are seemingly infinite. However, in practice a significant simplification of modelling carbonation depth in terms of time is expressed as (Czarnecki and Woyciechowski, 2015):

$$x = B - A\sqrt{t} \tag{2-24}$$

Where,

x = Carbonation Depth [mm]

A = Constant (dependent on the diffusion coefficient)

B = Empirical Factor (accounting the initiation period of carbonation)

The A and B variables can be combined to represent a vast number of environmental and/or material variables, however, the relationship between x and t is well supported throughout literature. An example of this is depicted in Figure 2-19 for different types of RAC (Hole, 2013).

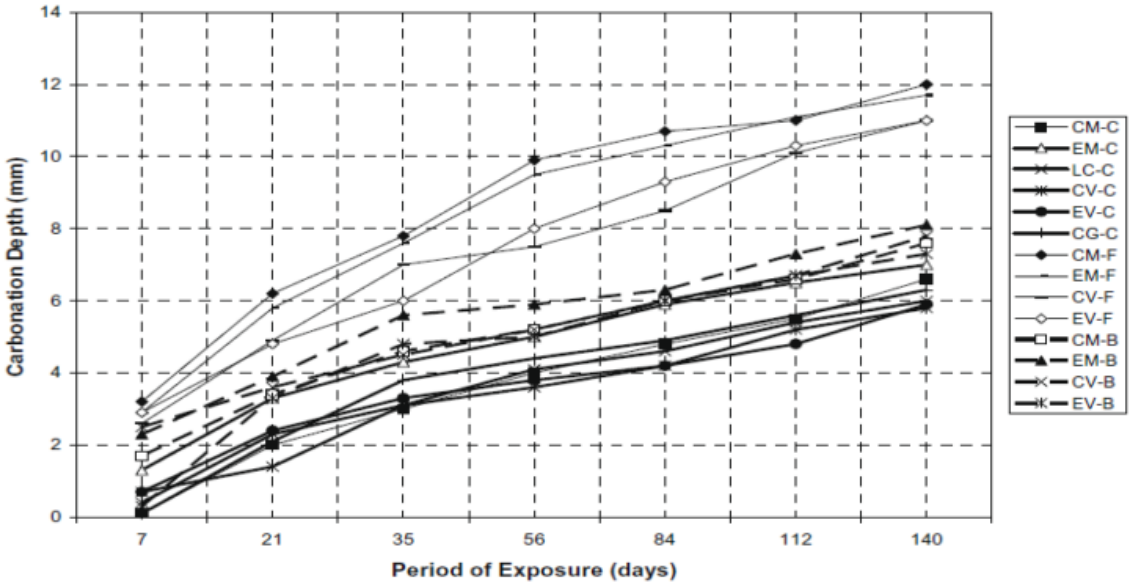


Figure 2-19: Carbonation Depth Relative to Exposure Time (Hole, 2013)

2.12 Summary of Literature

The literature review aimed at consolidating information regarding RCA as a pavement material in context of typical behaviours of bound and unbound pavement materials. Literature on the carbonation process and the potential threat it poses on the durability of bound materials was investigated to gain perspective of how RCA material would react to these conditions. Some fundamental aspects in the literature review will not be carried forward in

this research study, rather, it was presented here to provide a holistic view of the research topic.

It is clear that the mechanisms of carbonation are sensitive to many variables prove difficult to 'control'. It is an inevitable chemical reaction which comes with the use of bound materials and therefore should be considered in the design process as such. Precautionary construction measures can be implemented to control moisture and density properties of the material being used, however, as far as environmental control is considered, this is out of the hands of the engineer.

Research pertaining to the performance of RCA as that which is bound or an unbound material is limited and for this reason, the performance of these common pavement materials was reported on and related to that of RCA material. Characteristics of RCA and application thereof as a pavement material was shown to differ in density and WA properties from NA, which cause for concern regarding the durability aspects such as carbonation. Majority of the literature regarding carbonation was related to concrete and this was taken into consideration and interpreted, where deemed necessary.

In conclusion, from the research it was necessary to include some method of controlling extrinsic variables such as pressure, CO_2 concentration and temperature as far as possible. In terms of RH, preliminary methods proved difficult to control this specific variable and although it is accepted as being one of the most important variables influencing carbonation, it was not possible to control. Intrinsic variables such as grading, cement content and curing time was accepted as being important considerations to follow through.

CHAPTER 3: RESEARCH DESIGN AND METHODOLOGY

3.1 Introduction

The Research Methodology in this project is divided in two consequential parts. Phase A (Section 3-2 to Section 3-3) includes the research development and execution of laboratory testing and Phase B (Section 3-4) covers the measuring and analysis of test outcomes.

In Phase A, the experimental design process as well as the experimental plan implemented to achieve the research objectives of this research study. The experimental design process includes the development of an accelerated lab carbonation test method followed by a testing methodology. Because the material procurement and testing is needed in the lab testing development stage, chronologically, this part is discussed first and a schematic layout provided in Figure 3-1.

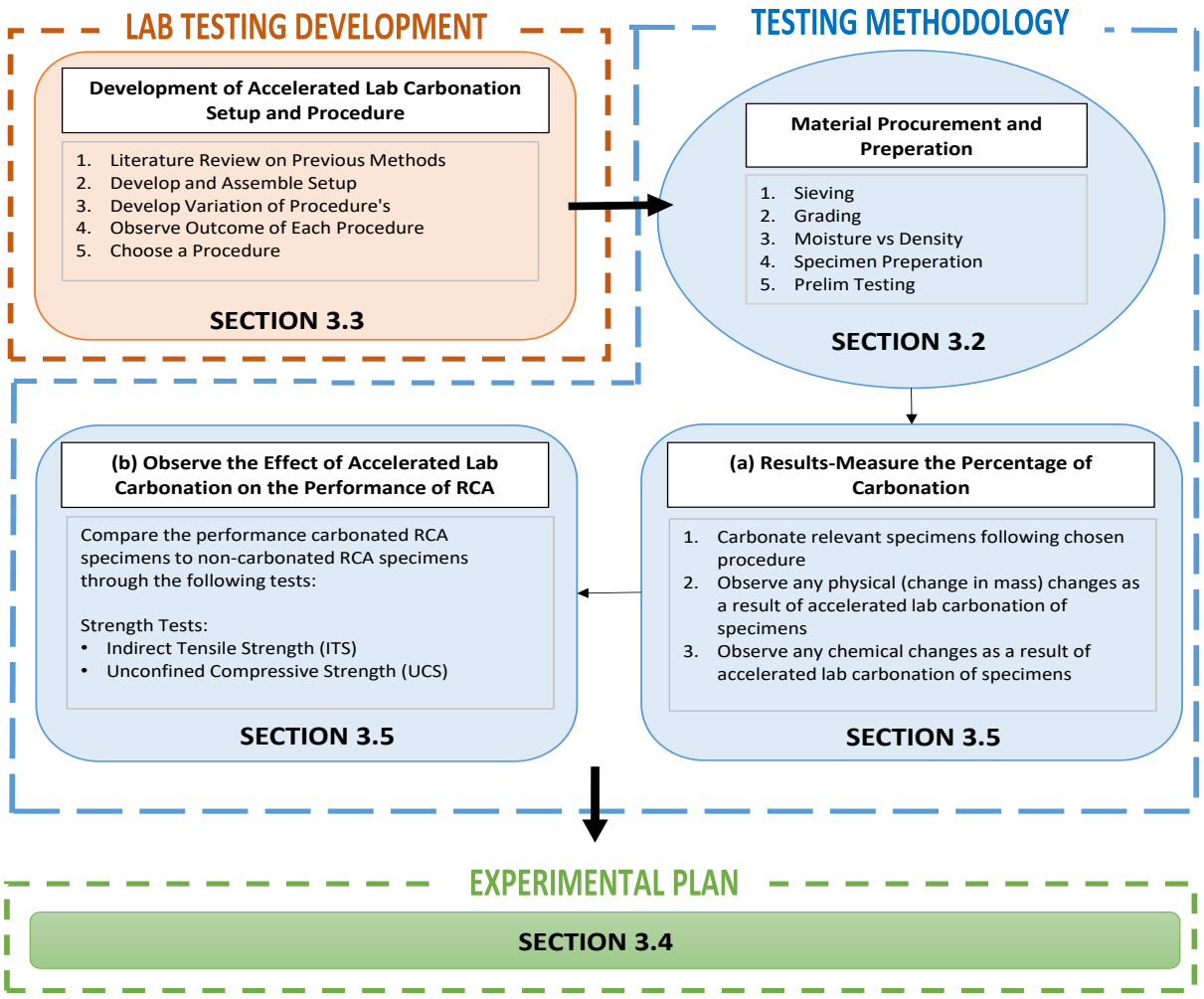


Figure 3-1: Schematic Layout of the Research Development and Experimental Design Process

The development of an accelerated lab carbonation method is founded upon a short literature review of methods previously used. A handful of adapted methods were implemented and the outcomes of each method was observed before deciding on an appropriate method.

The testing methodology can be divided into four main parts: (a) The first part discusses the material procurement and specimen preparation (Section 3.2), (b) the second part (Section 3.3) discusses the development of the carbonation chamber apparatus by the researcher and application of the carbonation process and (c) the third part includes the observed carbonation of the relevant materials and the development of a carbonation methodology process (Section 3.3). Subsequently the development of the Experimental Plan is developed in Section 3.4.

In conclusion, the methods used to measure the performance of RCA is introduced in Section 3.5 through (a) evaluating the percentage of carbonation, (b) testing the compressive strength and (c) tensile strength following the developed accelerated lab carbonation process (apparatus and method).

3.2 Material Procurement, Preparation and Testing

RCA was constituted to produce two material types based on the difference in grading. This material was produced from CDW which was sourced from the demolition of the Tulip Hotel in Cape Town. This building was constructed approximately 30 years ago and the RCA produced/recycled from this building is considered to be particularly 'old' but representative of typical material that would be demolished and utilised.

The material was transported by truck to Stellenbosch University where the concrete was screened from contaminants such as steel and/or masonry (holistic process provided in Figure 3-2). The pure concrete elements were further crushed, sieved and separated into various fraction sizes in accordance with the Standard Methods of Testing Road Construction Materials (TMH1, 1986). This allowed for reconstitution of the grading to ensure that variability in the grading is minimised.

Figure 3-2: Typical Procedure for Obtaining RCA from CDW

3.2.1 Crushing and Sieving

Where necessary, the vibratory hammer was used to break large concrete samples into more manageable portions. The material was passed through the jaw crusher a total of two times to ensure better angulation of the fractions and increasing production of fines, allowing for a better fit of the grading curve. The impact of primary crushing versus secondary crushing is shown Figure 3-3 below.

Figure 3-3: Fractions Obtained Through Primary (L) and Secondary Crushing (R) (Barisanga, 2014)

In some cases, it is necessary to air-dry material prior to sieving. This is to ensure that the material passes through the various sieves without clumping or blocking the sieves as a result of moisture contained within the material. Hence, the material is distributed evenly over a floor surface in a laboratory room which provides sufficient ventilation for the material to dry over a number of days. The material is then placed in sealed bags and moved to the sieving room. However, as will be shown in Table 3-2, complete dryness cannot be achieved in a realistic environment, and hygroscopic moisture is still present after this process.

Finally, a large-scale vibratory sieve is used to separate the materials into fraction sizes. These fractions are placed in separate sealed bags and labelled accordingly, before being moved to plastic bins in the laboratory material storage room.

3.2.2 Material Grading

The grading of a material has a direct influence on the strength of the final specimen. To achieve an optimum packing of the different size fractions, the Fuller Curve was used as a general guideline with adjustments made, as will be explained later.

The Fuller Curve is based on the following equation:

$$P = \left(\frac{d}{D}\right)^n \tag{3-1}$$

Where,

P	=	% of fraction finer than sieve
d	=	Aggregate size being considered
D	=	Maximum aggregate size to be used
n	=	0.25 and 0.5 for lower and upper limit of envelope, respectively

Notably, previous studies have shown that packing with a relative n-value of 0.5 will deliver optimal results (Nijboer, 1947). However with the intention of balancing initial grading results from the crusher and additional practical issues, a Fuller coefficient of n= 0.3 was used for the continuous grade RCA material. Two grading curves were selected for testing, namely, continuous grade and gap grade as given in Figure 3-4.

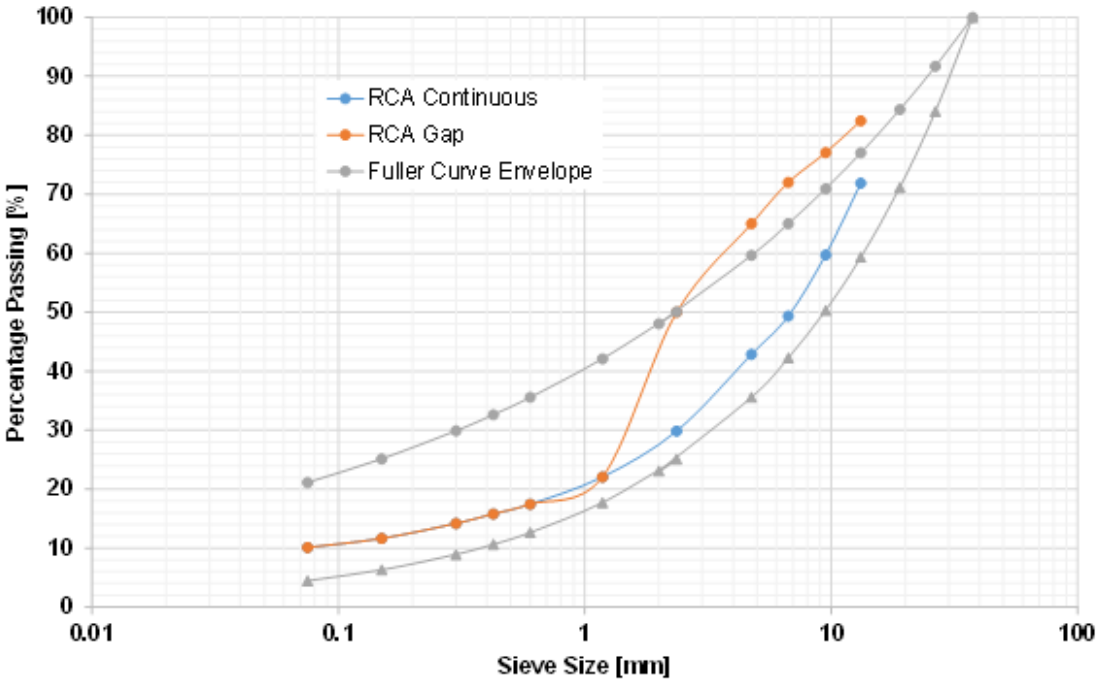


Figure 3-4: Design RCA Grading Compared to a G4 Grading Envelope

A shortcoming of laboratory testing is the small-scale apparatus used which limits the maximum allowable fraction size. Typically, the ratio between specimen diameter and maximum aggregate size, $d_{specimen}/d_{max\text{-}particle}$, is limited to a minimum of between 6-7 (Van Niekerk, 2002). This meant, for the purpose of this research study where the specimen diameters were 100mm, a maximum particle size of 13.2mm was used. Hence, an adjustment was made to the grading by implementing a method of substitution i.e. all material retained on the 19mm sieve being weighed and substituted by the same weight of material retained on the 13.2mm sieve was used. This method is commonly referred to as the add-back method. Van Zyl (2014) reported that the removal of the larger fractions and the replacement thereof

with the largest allowable fraction size allowable results in a material that best represents the material matrix to the full range of particle sizes and highest comparable behaviour.

3.2.3 Compaction

Compaction plays an important role in the performance of both bound and unbound granular materials. There is a direct correlation between the moisture content (MC) of the compacted specimen and achievable density. A density-moisture relationship can be established by applying equal compaction on material specimens containing various MC's. The maximum dry density (MDD) at the optimum moisture content (OMC) can be established where the parabolic-shaped graph reaches its turning point, as shown in Figure 3-5.

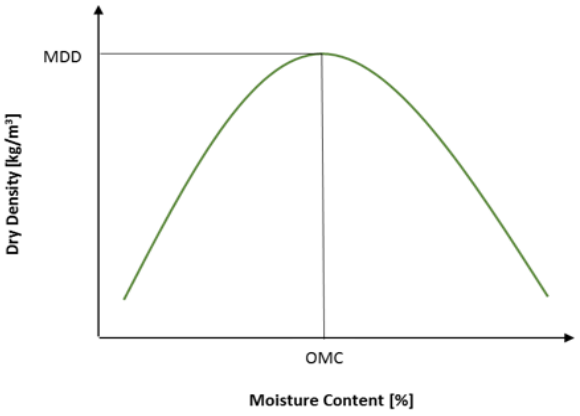


Figure 3-5: Typical Density-Moisture Curve

Table 3-1: Maximum Dry Density and Optimum Moisture Content for Gap Grade and Continuous Grade RCA Material

Mixture Properties	Gap Graded	Continuous Graded
MDD [kg/m^3]	2050	2150
OMC [%]	10	8,5

Method A7 of the TMH1 (1986) outlines the standard density-moisture relationship. This method incorporates the Modified AASHTO compaction method which applies impact energy. The density-moisture relationships for each grading curve had to be developed and from this, the universal MC was selected. This MC was applicable to all the relevant specimens and, where deemed possible, was maintained as such. The MDD and OMC used for both the continuous grade RCA and gap grade RCA are summarised in Table 3-1.

3.2.3.1 Challenges addressed during compaction

Due to the high absorption properties of RCA, the MC was found to be variable and adjustments were made accordingly during the preparation of the RCA specimens. The hygroscopic moisture content, MC_H, was measured to be ±2.5-3% when obtaining the moisture-density of both material grading's despite implementing a consistent and lengthy drying out regime. Through further inspection of this acute RCA property, the MC_H was found to vary substantially within a single material batch. The results of six MC_H tests performed from

the same material mixture for both continuous grade and gap grade RCA, are shown in Table 3-2.

Table 3-2: Measured Hygroscopic Moisture Contents from a Single Mixture for Gap Grade and Continuous Grade RCA

Hygroscopic Moisture MC_H (%)						
Sample #	1	**2**	**3**	**4**	**5**	**6**
Gap Grade	1.27	1.95	2.51	2.92	3.23	3.42
Continuous Grade	2.08	2.19	2.26	2.38	2.96	3.07

The results from Table 3-2 indicate the high variability of MC_H for both material grading types, with the gap grade RCA material exhibiting the largest range in variation. It should be noted that from this, even though a strict regime in the specimen preparation process was followed, significant variance was obtained when compacting the materials. As will be seen from the results to follow, this particular characteristic of RCA manifested in some variance of the resulting specimen densities, however, valuable and significant conclusions in the correlation between variables and carbonation were nonetheless observed.

High water absorption is a characteristic commonly associated with RCA. It also varies for different fraction sizes and is initially influenced by the crushing process, as well as climate factors throughout the lifetime of the RCA. Therefore, it was challenging to obtain the correct MC during compaction of the specimens. It seemed as though each batch of material had its own unique moisture requirements as in some cases it was found that the target OMC did not provide enough moisture and at other times it was too much. For this reason impromptu engineering judgment was applied while mixing each batch of material, followed by the preparation of each specimen.

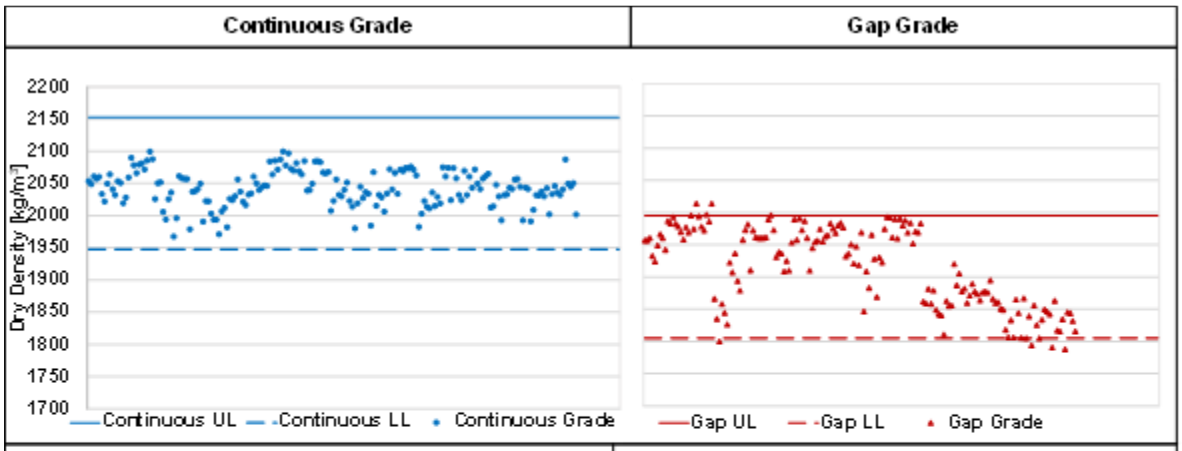
For all specimens prepared and tested the mixing moisture content and dry density after compaction was computed and noted. In addition, for the UCS specimens, the moisture content and pH-value after testing was measured. From these results, graphs were prepared showing the variability of the moisture content and the achieved density in relation to the target density of 2050 kg/m^3 and 2150 kg/m^3 and target moisture content of 10% and 8.5% for gap and continuous grade, respectively.

3.2.3.2 Dry Density Results

The achieved Dry Density (DD_{mix}) of each specimen prepared for testing is shown in Figure 3-6 for continuous and gap grade RCA. The Upper Limit (UL) and Lower Limit (LL) of each data set is plotted and represents a variation of ±5% in relation to the target DD. This is a high variation and it would have been best to keep this to a maximum of 2%, however, the

specimens were prepared over the course of a few months and it is believed that longer periods of storage and varying climate factors had a significant influence on the material properties, specifically that of the latent adhered cementitious product found on the larger aggregates. It must further be noted that although high variation in DD_{mix} presents itself across all curing times, this variation is narrowed down considerably when the specimens at individual curing times are considered.

The UL and LL for continuous grade RCA was calculated as 2153 kg/m^3 and 1948 kg/m^3, respectively; similarly for gap grade RCA 1995 kg/m^3 and 1805 kg/m^3. The data shows that the density of gap grade RCA is more sensitive to moisture variation than continuous grade RCA. As presented in Chapter 2 (refer to Figure 2-6), an aggregate skeleton that consists of a great amount of fines results in decreased density and is affected by adverse water conditions. The gap grade material presented in the scope of this research study is considered as such.



Dry Density at Mixing (DD_{mix})		Dry Density at Mixing (DD_{mix})	
Mean	2042 kg/m^3	**Mean**	1916 kg/m^3
Median	2041 kg/m^3	**Median**	1931 kg/m^3
StdDev	28	**StdDev**	61
Moisture Content at Mixing (DC_{mix})		**Moisture Content at Mixing (DC_{mix})**	
Mean	10.42%	**Mean**	12.22%
Median	10.48%	**Median**	12.17%
StdDev	0.99%	**StdDev**	0.99%

Figure 3-6: Summary of Dry Density and Moisture Content at Mixing

As explained earlier, the data shows very high standard deviations for both continuous grade (σ = 28) and gap grade (σ = 61) RCA material. It must be noted that overall the material density varies significantly, however, in terms of specimens prepared for specific curing times this variation was limited. This will be shown further on when the material properties of the individual specimen groups are analysed.

3.2.3.3 Moisture Content

The target MC of 8.5%, for continuous grade RCA, and 10%, for gap grade RCA, was exceeded on average by 1.42 % and 2.22 %, respectively (refer to Figure 3-7). This phenomenon is a reflection of the water absorption (WA) of RCA, also measured as the material's hygroscopic moisture content (MC_H), and the influence of the grading curve of RCA on the MC_H.

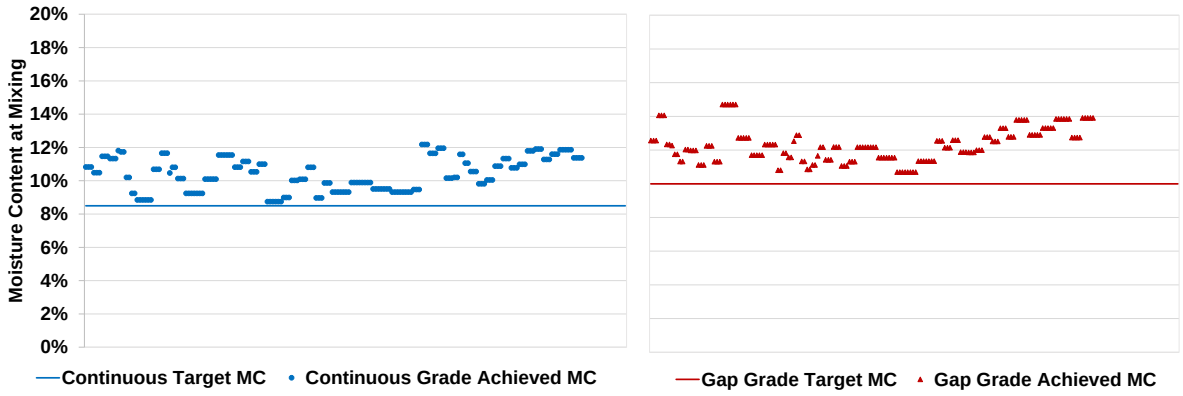


Figure 3-7: Achieved Moisture Content of All Prepared Specimens

MC_H is an imperative material characteristic of RCA and is influenced by a number of extrinsic and intrinsic factors. As mentioned earlier, the material grading curves were constituted through combining various proportioned fraction sizes. For the purpose of this research study, MC_H of the material grading was found to range between 2.08%-3.07% and 1.27%-3.42% for continuous grade and gap grade RCA, respectively.

Figure 3-8: Batch of Prepared Continuous Grade RCA Specimens Labelled and Sealed for 28 Days Curing. Placed in a 25°C Temperature Controlled Room

Following preparation and compaction of the material, the specimens were sealed and placed in a temperature controlled room for the required amount of curing time (refer to Figure 3-8). The curing time of RCA has a direct influence on the strength development, as with any unbound or bound material. Correct curing methods allows for the material to develop cohesion as well as provide a platform for the reaction of cementitious products, through efficient hydration.

3.2.3.4 Initial Consumption of Cement

Prior to the commencement of the main part of the experimental plan, preliminary indicator tests were performed to characterise the material in its bulk form. This included recording the Initial Consumption of Cement (ICC). The aim of the preliminary ICC tests were to provide a relative indication in the potential for self-cementation but more importantly, to determine realistically what would be practical additions of cement percentages, taking cognisance of industry practice but also achieving the full consumption needed to provide a fully stabilised material.

The ICC is the minimum cement quantity required to maintain a constant pH value after one hour. IDM general purpose cement (Grade 32.5N) was used as to stabilising agent along with distilled (pH = 7.0) water. The results of the ICC performed on both the Continuous Grade RCA as well as the Gap Grade RCA are shown in Table 3-3 below. The steps outlined in SANS 3001-GR57 were completed to obtain these values.

Table 3-3: Results of the Initial Consumption of Cement

	pH-Value					
Cement %	**0**	**1**	**2**	**3**	**4**	**5**
Continuous Grade	9.8	11.93	12.46	12.82	12.82	12.82
Gap Grade	8.72	11.76	12.24	12.47	12.47	12.47

It can be seen that both ICC results stabilised after 3% cement was added. It was decided, however, to use a cement content of 2% for all specimens as this is commonly the amount of stabiliser added to a granular material in practice and the pH-value of 12.2 is sufficient for a stabilised material. Although the outcome of the ICC results was not fully implemented in the scope of this research study, it was thought to give further insight to the adhered mortar of the RCA material to which no stabiliser was added. From the results it can be observed that the continuous grade RCA material has a slightly higher pH-value compared to that of the gap grade RCA.

3.3 Lab Testing Development

The objective of the accelerated lab carbonation procedure, for the purpose of this research study, is to achieve full carbonation of the relevant RCA specimens. It was considered more feasible to expose specimens to accelerated carbonation conditions in a lab setup as environmental carbonation is a very slow process and would prove more difficult to control and observe the carbonation phenomenon as a process.

3.3.1 Current Standard Accelerated Lab Carbonation (SAPEM, 2014)

The diffusion of CO_2 gas into material is the first process of carbonation. This process is governed by the material properties such as grading and active stabiliser content, as well as environmental conditions such has temperature, relative humidity, pressure and the concentration of CO_2. The second process of carbonation takes place within the pore structure of the material where material properties such as grading, age, available active stabiliser, as well as pore properties are the driving force behind the reactions taking place during this phase.

The accelerated lab carbonation procedure is outlined in SAPEM (2014), Chapter 3, Appendix A. In summary, a gas pipe connects a vacuum pump and a CO_2 gas to a chamber, this allows for removing of the gas present and replacing it with pure CO_2 gas. The vacuum phase (removal of the present gas) is maintained for 10 minutes, followed by the inlet of pure CO_2 gas for 10 minutes until the chamber is deemed 'full' (reaching equal to or above atmospheric pressure conditions). These steps are repeated three times, followed by a final vacuum after which the chamber is filled with water. It is understood that this procedure was selected in an effort to induce a pressure gradient within the chamber which encourages pore pressure build up. Both the permeability of a material and the pressure gradient influences the rate of material transfer and thus, the rate of carbonation (Sun, 2010). Furthermore, no comment can be made regarding the reason for the inlet of water as the final stage. I am not too sure what more to say here…as there is not much insight to the 'physics' of this procedure

3.3.2 Development of the Research Accelerated Carbonation Lab Apparatus in this research

Dovetailing on the standard procedure, the Research Accelerated Carbonation Lab Apparatus (RACLA) was developed. An important factor to consider additionally to the standard method described in SAPEM (2014) is the ability to control the CO_2 inlet (magnitude and concentration) as well as the relative humidity. Both of these variables could be measured and controlled in the RACLA. In the next two sections the development of the apparatus and the application method is discussed.

The apparatus includes three glass desiccators which are used as carbonation chambers (See Figure 3-9). Bespoke designed glass chambers (Figure 3-10) are inserted to the lids of the glass desiccators and house the (gas and vacuum) pipe inlet and the following Vernier measurement tools:

- Vernier Gas Pressure Sensor
- Vernier Temperature Probe
- Vernier Carbon Dioxide Meter (Figure 3-10)
- Vernier Relative Humidity Sensor (Figure 3-10)
- Gas pipe to allow for the inlet of CO_2 and the attached vacuum pump

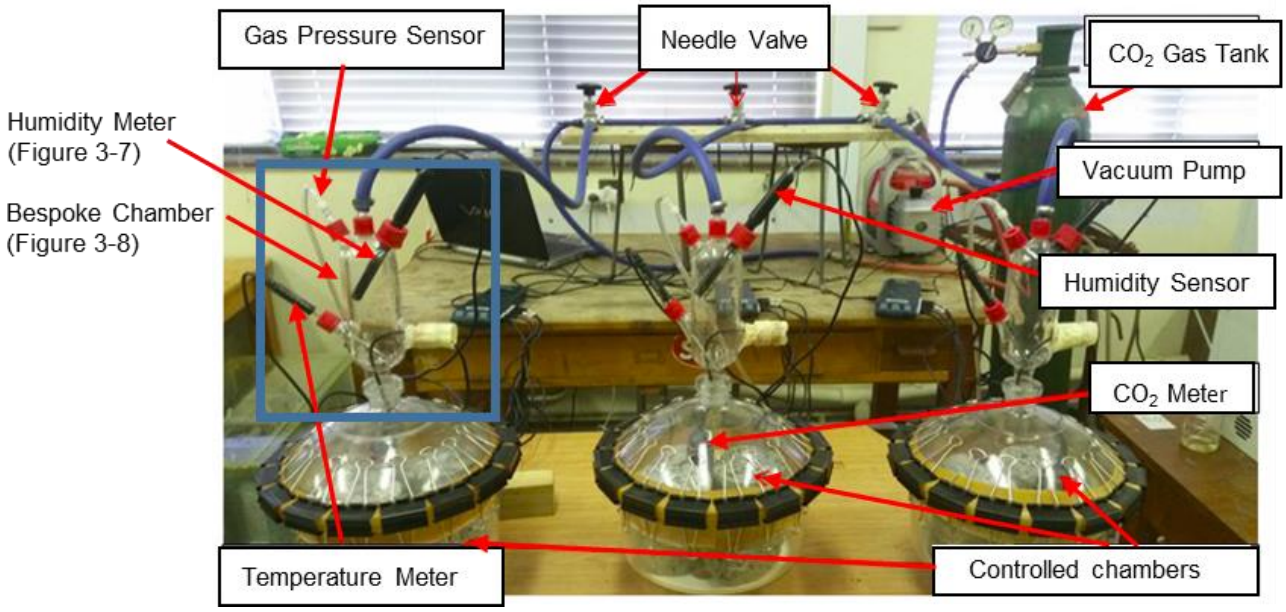


Figure 3-9: Research Accelerated Lab Carbonation Apparatus Developed by Researcher

The gas pipes are connected to the glass chambers and fitted with a needle valve to control the flow of gas as can be seen in Figure 3-9.

Figure 3-10: Vernier CO2 and Relative Humidity Meter (L) and Bespoke Glass Blown Chamber (R)

A process flow schematic is provided in Figure 3-11. Here the input and output flow of the RACLA can be observed. The gas pipe is connected in series to an 80kPa vacuum pump on one side and a CO_2 gas cylinder on the other side. The data logger connected to each chamber, which assist with controlling and measuring the extrinsic factors, is also shown in this flow diagram.

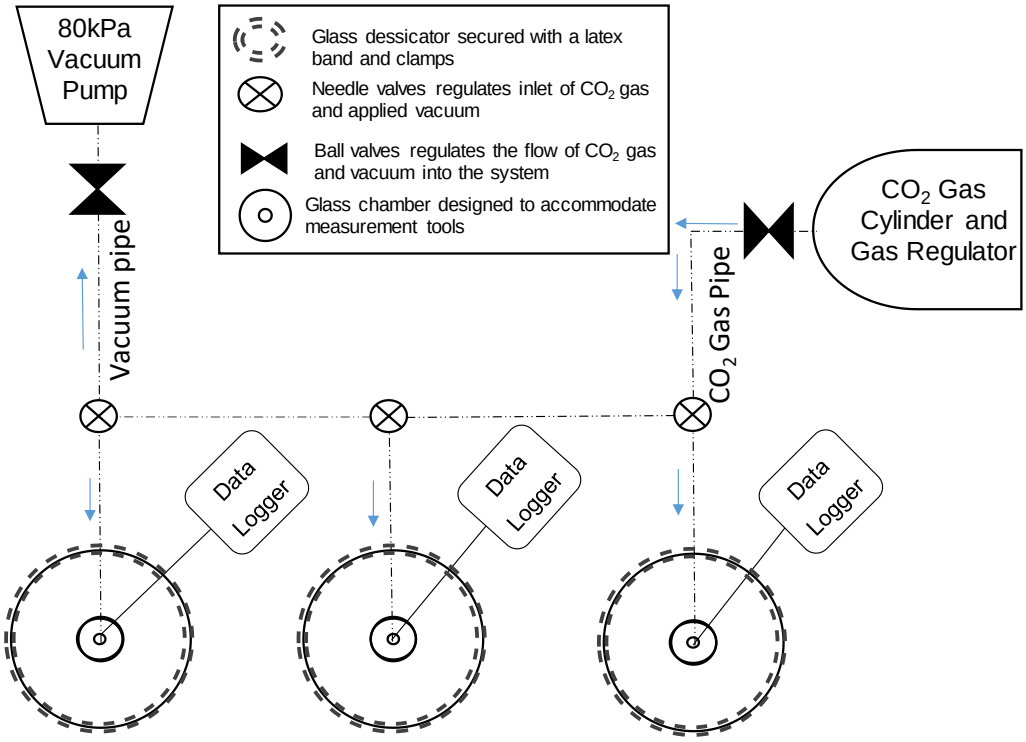


Figure 3-11: Schematic Flow Diagram of the RACLA

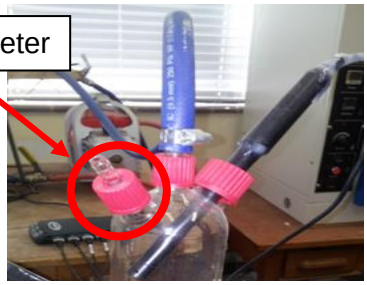
The chambers designed for this research study purposefully do not accommodate the inlet of water and therefore the final water 'flushing' stage was excluded, as this would hinder measurement tools during the carbonation process. The consequence of excluding this phase is understood to not significantly influence the carbonation of the specimens. It is understood that this stage was implemented in the relevant method purely to dissolve excess hazardous CO_2 gas left in the chamber.

As part of the process of developing a research apparatus and method to apply carbonation to reach the objectives of this research study, many troubleshooting mitigation measures had to be taken. This included some adjustments prior to the layout and configuration seen here. Some of the main challenges and the follow-up solutions are briefly encapsulated in Table 3-4(a) and Table 3-4(b), presented on the next few pages.

Table 3-4 (a): Troubleshooting in the Development of the RACLA

Problem Description 1: Placement location of humidity, temperature and CO_2 gas sensor:

In the initial design all meters were placed in the bespoke glass chamber. It quickly became apparent that, particularly the CO_2 meter, gave erratic results when the vacuum and CO_2 inlet cycles were repeated.



Solution 1: CO_2 meter is placed within the desiccator

A sensitivity analysis was performed on all meters to determine the stability of readings. Only the CO_2 meter appeared to show erratic results in comparison to placing it in the bespoke chamber as opposed to in the desiccator itself. The conclusion was made that the concentration of CO_2 accumulated within the desiccator and did not necessarily always fill up the bespoke chamber. The reason for this could be attributed to the difference in molecular mass of the CO_2 [M = 44g/mol] molecules compared to that of Air [M = 29g/mol].

Problem Description 2: Sealing of desiccators

In the initial design, it was thought that the desiccators itself would provide sufficient sealing throughout the carbonation process. Results of the pressure gradient within the chambers were significantly variable and it was identified that the rims of the desiccators were not flush.

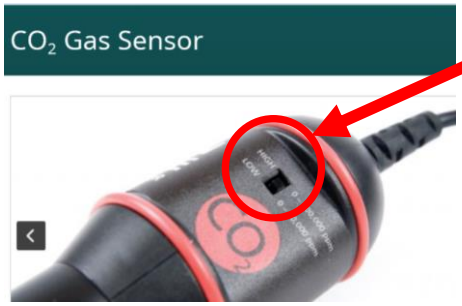
Solution 2: A two-fold sealing process was applied to the rims of the desiccators

The initial solution included the application of a lubricant alongside the rim of the desiccator. This did not deem sufficient and leakages were still experienced. Consequently, a rubber membrane was positioned to envelope the rim, which provided significant improvement on the variability of the measured gas pressure. An additional measure included crocodile clamps which were situated on the circumference of the rim, upon the rubber membrane. The staged application of these numerous crocodile clamps, allowed for evenly distributed applied forces on the rim and ensured that stress concentration did not occur where the rim was not flush. This aided in equidistant application of sealing pressures.

Table 3-4 (b): Troubleshooting of the RACLA development (continued)

Problem Description 3: Sealing of the bespoke glass chamber:

The problem of leaking with the bespoke chamber was two-fold. Firstly inlets could be sealed around instrumentation, but a specific challenge was the CO2 meter where flow was regulated through the apparatus.



Although the front part that is within the chamber is sealed against the chamber so that air does not escape but then air still escapes through this little switch

Solution 3: CO_2 meter is placed within the desiccator:

Initially the whole was sealed off, but this still gave erratic results. We reverted back to Solution1 which solved both the dealing and the spread of CO2 within the desiccator itself.

Problem Description 4: Could not control the inlet of CO2 into the system:

The control of the flow of CO2 into the chambers from the gas tank was a challenge.

Solution 4: Application of the correct type of valve onto CO2 pipe feed:

Many types of valves were researched, but the only valve that provide sufficient sensitivity to inlet of CO2 was the application of a needle valve just before each desiccator. The needle valve assisted in controlling the pressure flow.

It is apparent from these problems that the leakage challenges, which seemed like the least significant issues, rendered the greatest setbacks. Furthermore, it highlights the importance of the adapted measuring meters (CO_2, relative humidity, and temperature) to keep control of the extrinsic variables within the chamber.

3.3.3 Developing the Method for Accelerated Carbonation in the Laboratory

The aim of exposing the specimens to CO_2 is to achieve a full range carbonation (as a percentage) of the specimens' volume. In other words, the variables must be measured against each other with the specimens being most sensitive to carbonation exhibiting 100% carbonation and those least sensitive to carbonation to have much less carbonation (0-10%). It was decided to perform variations of Paige-Green's (1990) proposed method and choose the one which showed the highest degree of carbonation of the specimens with 2% added

cement, as these would be the most resistant to carbonation. As mentioned previously, it was important not to devise a method that would collectively carbonate all specimens to the maximum degree but rather have some sensitivity to the degree of outcome so that variables could be measured against each other.

A total of three variations including the standard method (Method A) and two variations (Method B and C) were investigated. The variations were based on changes to the individual vacuum and gas inlet phases, in terms of extension of time as well as the number of repeats of these phases, as can be seen in Figure 3-12. In all cases the CO_2 inlet phase was controlled at ±100 000ppm at a pressure of ±115kPa and the vacuum phase showed CO_2 concentrations which varied between ±100-2000ppm at pressures <10kPa.

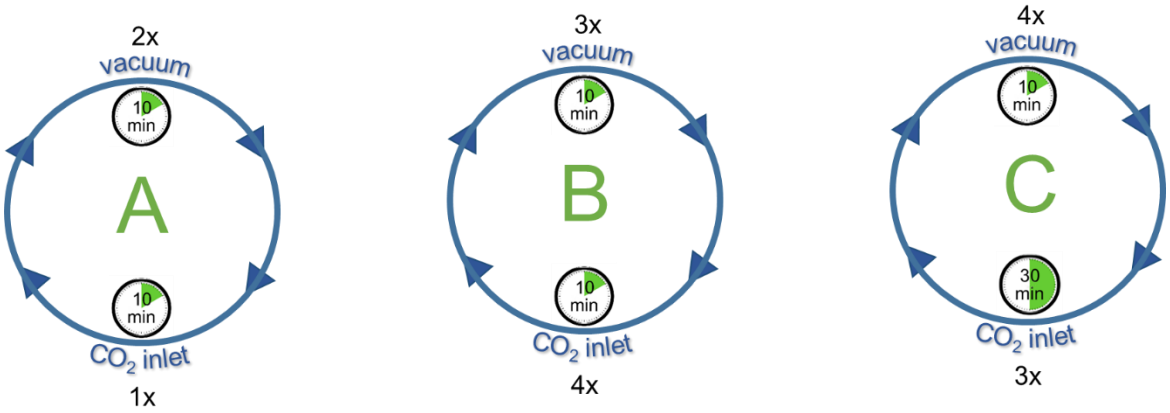
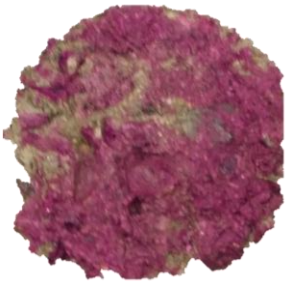
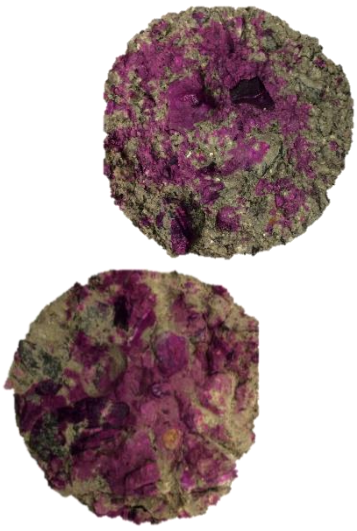


Figure 3-12: Sequence of three applied methods – Method A, B and C

It should be noted that Method A differed from Method B and C in that the vacuum pump was switched off during the vacuum phase, whereas in Method B and C the vacuum pump remained switched on for the duration of the vacuum phase. Method C was decided as the chosen accelerated lab carbonation method and this was based on the observed degree of carbonation of the respective specimens.

Table 3-5 includes a typical general outcome from each method. It is clear from the results that Method A entirely carbonates all specimens, both for 0 and 2%, Method B is poor in carbonating the specimens and Method C appears to distinguish between variables (0 and 2%, gap and continuous) when carbonating which allowed for quantifiable conclusions between these variables.

Table 3-5: Visual variances between procedures

Method	0% Cement Content	2% Cement Content
A		
B		
C		

3.4 Experimental Plan

After the development of the RACLA and the carbonation method, the experimental plan could be established. An experimental plan had to be developed that would allow for the comparison of the performance of Carbonated (C) RCA specimens with the performance of Non-Carbonated (NC) RCA specimens. Due to time constraints, only one source of RCA material was investigated. The variables of this material included two grading types, two added cement contents and three different curing durations.

The experimental design can be subdivided into the following sections namely; Material, Grading Curve, Specimen Size, Compaction Method, Conditioning of Specimens, Performance Tests and Performance Properties. A short discussion of each follows.

Material: As mentioned, due to time constraints as well as ongoing parallel research focused on RCA, at Stellenbosch University, only one representative material source was selected.

Grading Curve: To observe the influence of grading curve on the carbonation potential of RCA, the experimental design incorporates two grading curves. The first grading curve (referred to as continuous) is based on the grading envelope of a typical natural gravel. For this grading curve, the scalp-add-back method was incorporated through removing all particles retained on the 19mm sieve and adding the mass equivalent, to the retained particles on the 13.2mm sieve. The second grading (referred to as gap grade), was a manipulation of the continuous grade curve. It was decided to include more of the coarse fractions in an attempt to create voids within the macro-structure of the material.

Specimen Size: Based on the chosen performance tests, three specimen sizes were selected. These include a typical UCS Specimen of 100mm diameter with a height of 150mm, a typical ITS Specimen with a diameter of 100mm and a height of 110mm.

Compaction Method: All layers of each specimen type were compacted to refusal with the vibratory hammer. Compacting to refusal implies that the hammer is stopped once the desired layer height is achieved. The difference in compacting the various specimens is the number of layers that are compacted for each. The UCS specimens are compacted in three layers of 50mm height each. The ITS specimens are compacted in two layers of 55mm each.

Curing: All specimens are placed in plastic bags immediately after compaction and the plastic bags are closed tightly with an elastic band. They are placed in a 25°C temperature controlled room and remain there for 1, 7 or 28 days.

Conditioning: Roughly half of the specimens are exposed to accelerated lab carbonation 'conditioning'. The specimens are exposed to these conditions on the final day of curing, for the specified procedure time.

Performance Tests: To compare the performance properties of both carbonated and non-carbonated RCA Specimens in terms of strength, both the Unconfined Compressive Strength (UCS) Tests and Indirect Tensile Strength (ITS) Tests were performed. Tests are used to determine the influence of carbonation on the measured specimens.

Performance Properties: Results from UCS tests are used to evaluate the influence which carbonation has on the compressive strength of RCA by comparing these results to the same test performed on non-carbonated specimens, the pH of each UCS specimen are also taken into account. The ITS tests are used to evaluate the influence which carbonation has on the tensile strength of the RCA specimens.

The full experimental plan is illustrated in Figure 3-13 and Figure 3-14.

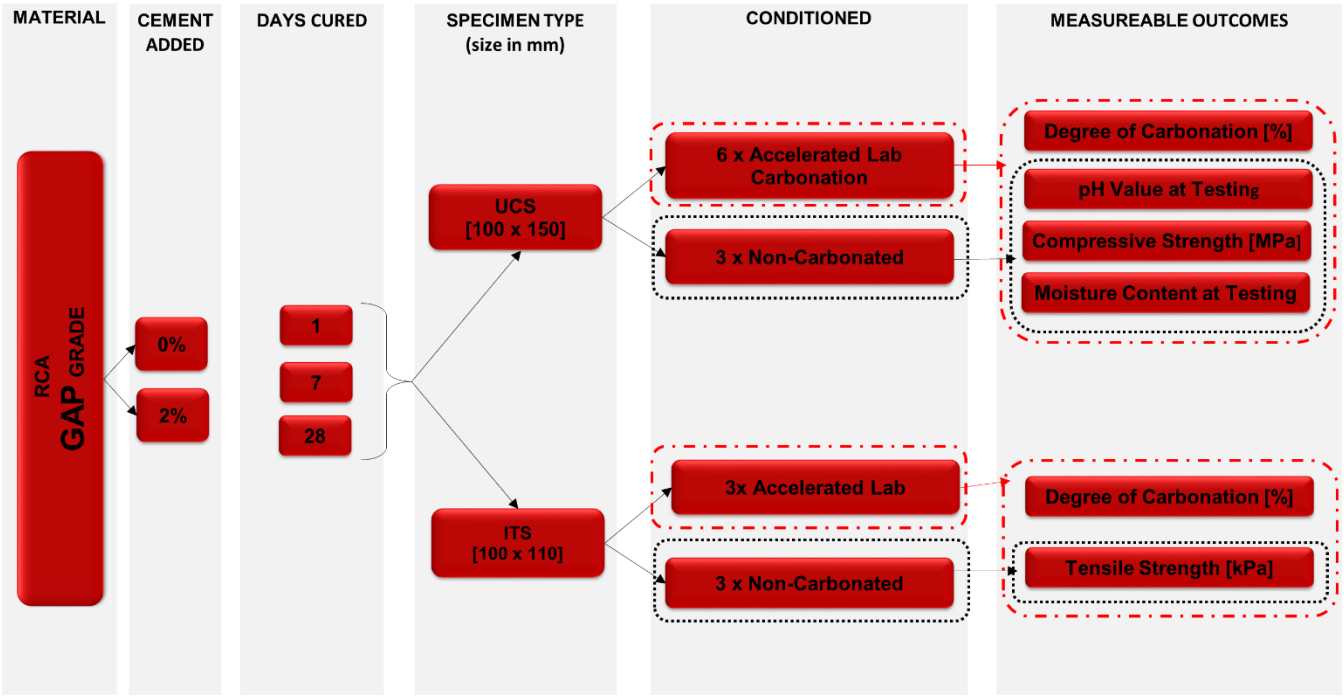


Figure 3-13: Experimental Plan-RCA Gap Grade

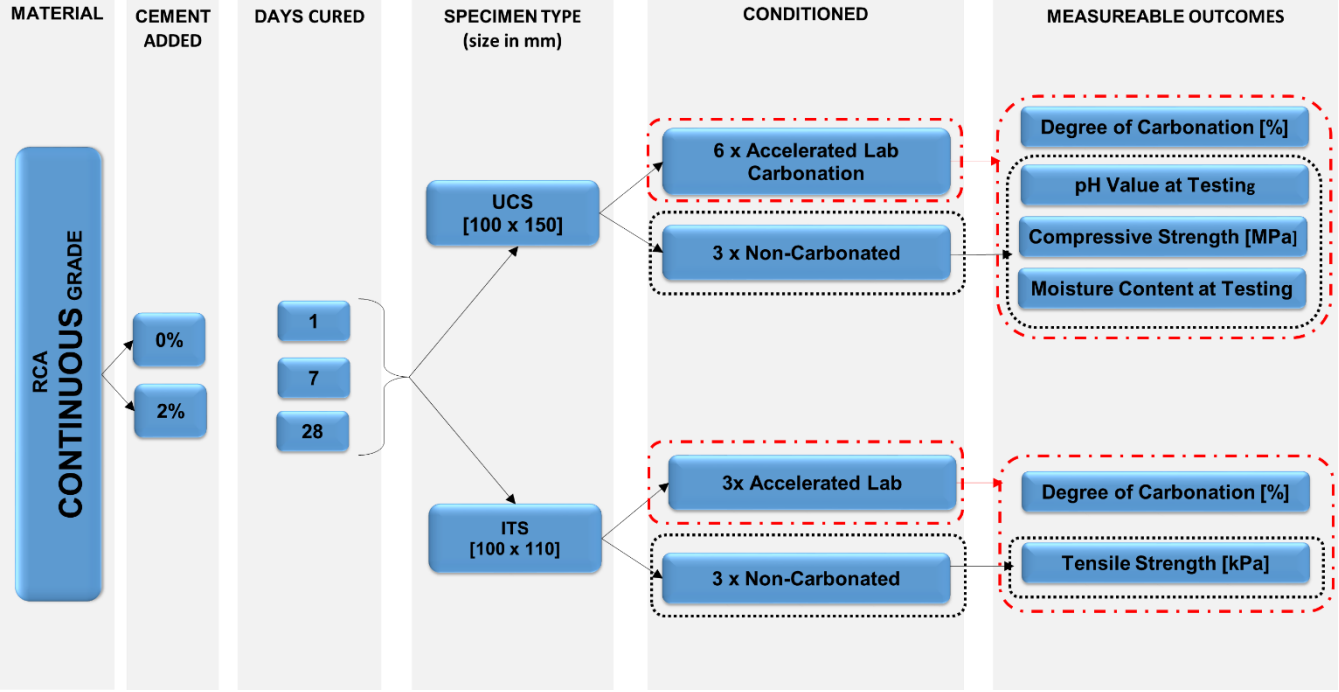


Figure 3-14: Experimental Plan-RCA Continuous Grade

The experimental design allows for the investigation of the influence of carbonation on the performance properties of RCA as a pavement material. This is done through comparing UCS, ITS results from the relevant tests performed on carbonated specimens to those of non-carbonated specimens.

3.5 Measurable Outcomes

Following the relevant curing time of 1, 7, and 28 days under a controlled temperature of 25°C, the specimens are placed in the carbonation chambers. It must be noted that the specimens were cured for the same period of time, under the same conditions as specified by the chosen accelerated carbonation procedure. However, the specimens were exposed to accelerated carbonation at the relevant stages of curing as initially stated.

The first leg (Approach 1) of the accelerated carbonation procedure involves placing two UCS specimens in each of the three chambers. One of the specimens contain no added cement stabiliser and the other contains 2% added cement. The aim of this leg of the procedure is to eliminate variable's related to the various specimen types, thereby, isolating the influence which the addition of cement would have on the degree of carbonation.

The second leg (Approach 2) of the accelerated carbonation procedure involves placing one of each specimen type, namely; UCS and ITS in each chamber. Each of these specimens contain the same amount of added cement.

3.5.1 Percentage Degree of Carbonation

The degree of carbonation was indicated by spraying phenolphthalein on the specimen subsequent to the application of the relevant test. The carbonation of each specimen was observed by visual inspection and noted accordingly. There was often little indication of a clear depth of carbonation and rather an overall degree of carbonation was observed in terms of percentage and configuration. Figure 3-15 represents the typical connotation associated with the various configuration of fuchsia-pink spots exposing the active material still present after carbonation of the specimen.

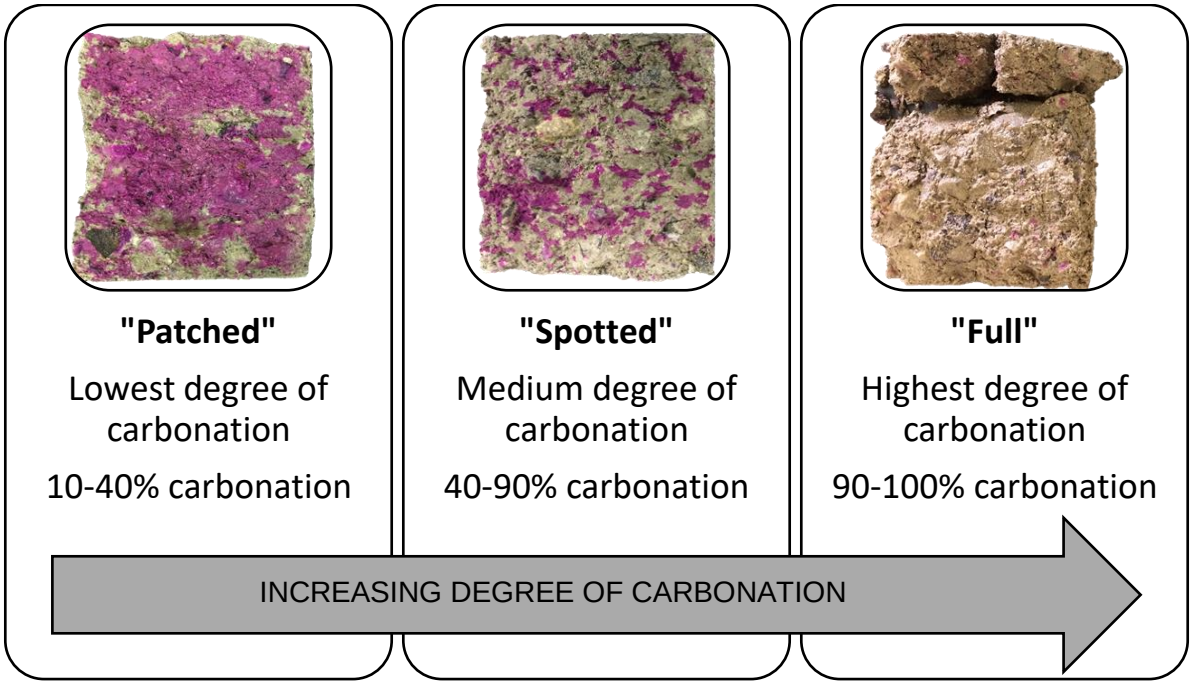


Figure 3-15: Typical Observation of the Degree of Carbonation of Specimens

In some cases, the use of the above description of the degree of carbonation was insufficient as the percentage of carbonation delineated too broadly. It was also recognised that a more explicit method of identification of the degree of carbonation was needed. All images can be referred to in Appendix B.

A two tiered systematic approach was used to identify the degree of carbonation. Firstly a software programme, namely JImage, was used that could connect a certain colour of pixel as a percentage of the whole image. This initially would have been the only approach as it was deemed to be the most accurate in measuring differences. However challenges were faced with the approach that included:

- Photo shades were different depending the lighting/shadows at the time

- Photos had to be taken by two different cameras (cellphones) due to unforeseen circumstance which meant that colour scales were vastly different.
- This meant that percentages would differ as a “light colour of pink” in one set of photos would be a “lighter grade of carbonation” but on the second set of photos would be because of the colouring shades of the camera.

This method was used as a stepping stone to the second procedure. This included using results from the photo analysis as a basis and ranking the pictures of the carbonated specimens from high to low in a visual exercise by taking the following steps:

- Observing the current ranking done by the camera and reorganising where outliers were present
- Delineating these into sub-groups of 0-10%, 11-20%, 21-30% up to 91-100%.
- After these groups were delineated, each group was delineated further for narrower bands.
- The process was followed by four independent reviewers before this was consolidated.

3.5.2 Chemical Changes as a Result of Carbonation (pH value)

Chemical changes were observed by measuring the pH of the UCS specimens. Method A20 of TMH1 (1986) was implemented and followed accordingly. The pH value indicates the concentration of the hydrogen ion, $[H^+]$, in a suspended solution of 30g of material passing the 0.425mm sieve.

3.5.3 Unconfined Compressive Strength

Subsequent to enduring accelerated carbonation, each specimen was tested in terms of the UCS and ITS. These tests were selected to measure the influence of carbonation on the strength properties of RCA. The strength tests (UCS and ITS) are carried out as part of the mix design procedure to establish an appropriate stabilising agent (SAPEM, 2014). The non-carbonated specimens are considered as ‘benchmark’ specimens in terms of the strength tests performed on them.

Selected UCS Specimens were sawn to produce two specimen types with heights of 110mm and 40mm. The specimens of 110mm height underwent UCS testing and those of 40mm height were used as control specimens to measure the degree of carbonation. Furthermore, the permeability specimens were endured ITS testing in addition to permeability testing. For ease of reading, it was decided to discuss the relevant tests in the order as below.

Conventional Unconfined Compressive Strength (UCS) tests were conducted in accordance with SANS 3001-GR53 however the specimens were tested unsoaked. The UCS is generally

considered as the most imperative mixture design index (Xuan *et al.*, 2012). The UCS result is determined using the following equation:

$$UCS = \frac{1000\ x\ F}{\pi\ x\ r^2} \tag{3-2}$$

Where,

UCS = Unconfined Compressive Strength [MPa]

F = Peak Force required to crush the specimen [kN]

r = Radius of Specimen [m]

This test was used to measure the self-cementing property of RCA, indicated by an increase in strength of the benchmark specimens at 1, 7, and 28 days of curing. In addition to this, the influence of carbonation was measured by observing the change in strength measured by the UCS of carbonated specimens against the results obtained from the benchmark specimens.

Following the UCS test, the crushed specimens were separated into two portions. One of which were further broken and placed in the oven in a moisture tin. The moisture content of each individual specimen at time of testing was measured by weighing the material prior to placing in the oven as well as after 24hrs of oven drying at 110 °C.

The second portion of the crushed UCS specimen was used to measure the pH value of the specimen at the time of testing. The obtained portion of the UCS specimen was further broken and sieved with a 0.425mm sieve. A mass of 30g of the material passing the sieve was added to 75ml of distilled water in a closed beaker. The beaker was left over night in a temperature controlled room (T = 25°C) and the pH-value was then measured.

3.5.4 Indirect Tensile Strength

The Indirect Tensile Strength (ITS) Test apparatus applies a load to the curved sides of a specimen causing failure. The ITS test was followed in accordance with SANS 3001-GR54. The ITS result was calculated using the following equation:

$$ITS = \frac{2\ x\ P}{\pi\ x\ H\ x\ D} \tag{3-3}$$

Where,

ITS = Tensile Strength [kPa]

P = Peak Force [kN]

H = Height of Specimen [m]

D = Diameter of Specimen [m]

Paige-Green (2015) mentions that the durability of stabilised materials is more closely related to the ITS than that of the UCS. However, both the UCS and ITS tests were decided as measurable outcomes to observe the influence which carbonation has on the compressive and tensile strengths of the material.

3.6 Analysis of results

The process for analysis of results are provided in greater detail in the next chapter. It includes a systematic evolution of the understanding of carbonation and the impact which the intrinsic factors have on the measurable outcomes. The analysis process includes (a) evaluating the degree of carbonation and how this correlates to the variables (b) measuring the change in UCS and ITS as a result of carbonation. This process is necessary as the method for degree of carbonation remains a visual exercise and it was deemed necessary to establish a quantifiable method that could represent carbonation, in this case UCS and ITS, which could then quantifiably be connected to the variables. Following these steps of the analysis process, (c) statistical correlations are determined for further use.

3.7 Conclusion

This chapter described the development of the Research Methodology which was followed. It included the new development of the RACLA apparatus, including the associated test method that would reach the objective of the measurement needed. The experimental layout and the planned outcomes are also discussed.

CHAPTER 4: ANALYSIS AND DISCUSSION OF RESULTS

Chapter 4 and Chapter 5 presents the interpretation, analysis and discussion of the test results relevant to the experimental design. A flow chart showing the analysis process followed to achieve quantifiable results is illustrated in Table 4-1.

The first part of the analysis, includes the (1) evaluation of the degree of carbonation to determine if different ranges of carbonation can be identified. Following this outcome, the UCS is used to quantify the correlation between variables in both non-carbonated and carbonated states. This analysis is performed in two chapters:

(2) Chapter 4 presents the preliminary analysis which investigates the variables independently from each other in a methodological as well as a statistical approach.

(3) In Chapter 5 the non-linear models and interdependency of the variables is considered, initially for the whole data set and later delineated further into curing time.

An analysis is performed in order to determine the correlation between the UCS and ITS of non-carbonated and carbonated material, in order to better describe the resistance before and after carbonation.

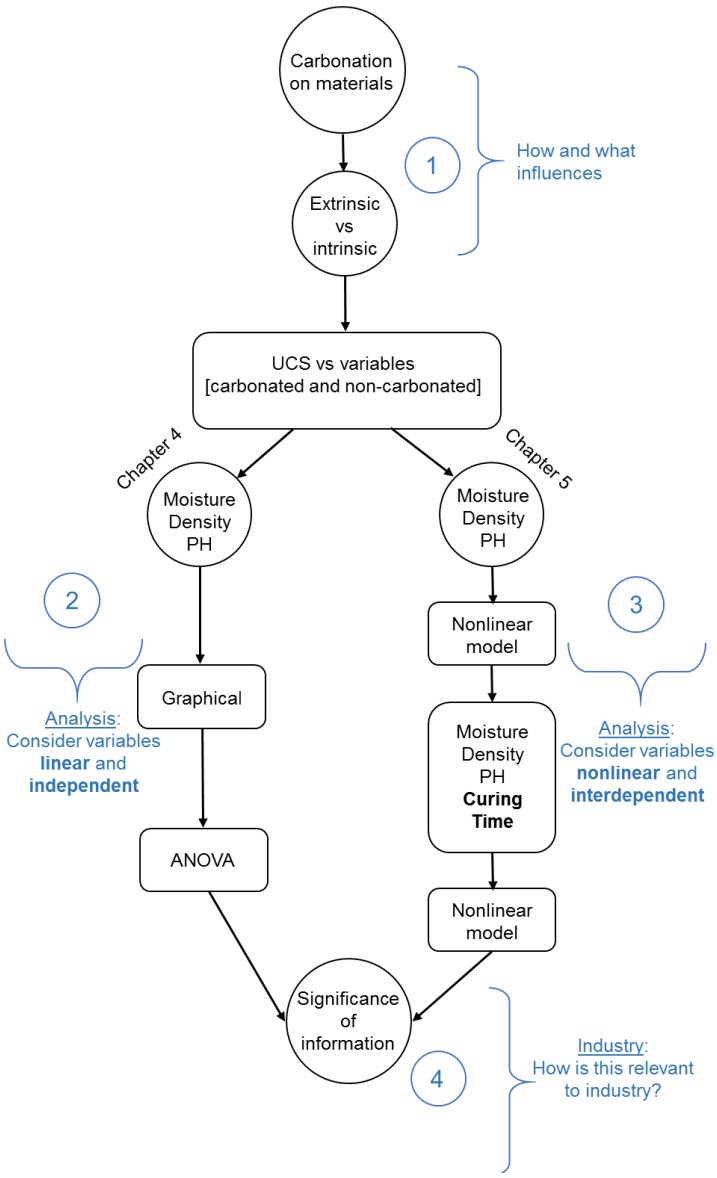


Figure 4-1: Summary of Analysis

(4) Thereafter, Chapter 6 outlines the significance of the developments and the importance which these findings could have on industry. All chapters are summarised in terms of conclusions.

4.1 Results of the RACLA – degree of carbonation

Specimens to be used for three different types of outcomes results were exposed to accelerated lab carbonation conditions. These included UCS, ITS specimens and a third set which was used as control specimens (for other based outcomes not reported in this research but by which degree of carbonation can still be measured against as this was prepared simultaneous to the others as explained below). The results of this carbonation process and the influence of that of the intrinsic factors are discussed here taking cognisance of the extrinsic factors as is described in Section 4.2.1.

4.1.1 Visual Inspection of the Carbonation of Various Specimens

As discussed in Chapter 3, extrinsic factors were kept uniform/constant as far as possible. This included the consideration of direction, location and sequential placement of the various specimens. All specimens maintained a diameter of 100mm, however, varied in height and therefore had varying Total Surface Area's (TSA's) when exposed to CO_2. As discussed in Chapter 2, the first phase of carbonation is dependent on the diffusion of CO_2 gas into the material. It is understandable that, amongst other variables, the TSA will have an influence on the diffusion constant and it is therefore expected that the various specimen types will carbonate at different rates. This is supported by Fick's second law of diffusion (equation(2-8). It can be said that durability is a function of carbonation and furthermore, carbonation is a function of multiple variables that can be classified as two major groups, environmental variables (extrinsic) and material (intrinsic) variables. This can be illustrated with a general equation as follows:

Durability of bound material = f(Carbonation, other variables)

Where,

Carbonation = $f(x_1, x_2)$

x_1 represents the sample space of extrinsic variables

x_2 represents the sample space of intrinsic variables

It was therefore expected that carbonation of the specimens at hand would be directly influenced by the cement content, grading type and the TSA of the specimen. To be able to "normalise" the TSA influence a two-part exercise including two accelerated lab carbonation approaches was undertaken. The first approach involved the placement of two UCS specimens of 0% and 2% cement content in a single chamber, in this case the TSA remains equal. These specimens were of the same material grade and had been cured for equivalent days. This approach disregarded the influence of TSA on the degree of carbonation in the horizontal direction and allowed for the influence of variables, such as cement content and grading, on carbonation to be further investigated under equal TSA's. In addition care was

taken on where percentage carbonation would be measured, i.e exactly in the centre (taken in the vertical direction) of the specimen. Therefore, carbonation of the specimen at the top and the bottom was not accounted for in the measured results.

The second approach involved the placement of three specimen types being, a UCS, ITS and control specimen within the same chamber. These specimens consisted of varying TSA's, with the control specimen being the smallest. However, they were of equal cement content, comprised of the same material grading and were cured for the same time duration. The objective of the second approach was to observe similarities in the way in which various specimen types, in terms of TSA, carbonate under controlled environmental conditions in order to correlate the different measurable ITS and UCS for example against each other.

Few instances exhibited clear carbonation depths and, as discussed in Chapter 3, this lead to having to rate the degree of carbonated material based on a ranking system. A total of 138 images were printed and ordered from the most carbonated to the least carbonated specimens. An indication of full, 100%, carbonation consisted of a specimen that showed no visible fuchsia-pink areas after being sprayed with the phenolphthalein indicator. Specimens considered to be non-carbonated instead presented an entire area consisting of fuchsia-pink material. Following this arrangement, a percentage was attributed to groups of specimens that indicated similar degree of carbonation (the detailed delineation process is discussed further in Chapter 3). From this, a range of degree of carbonation was allocated to each specimen according to material grading, cement content and curing time and a visual presentation of the distribution of specimens reported in Figure 4-3.

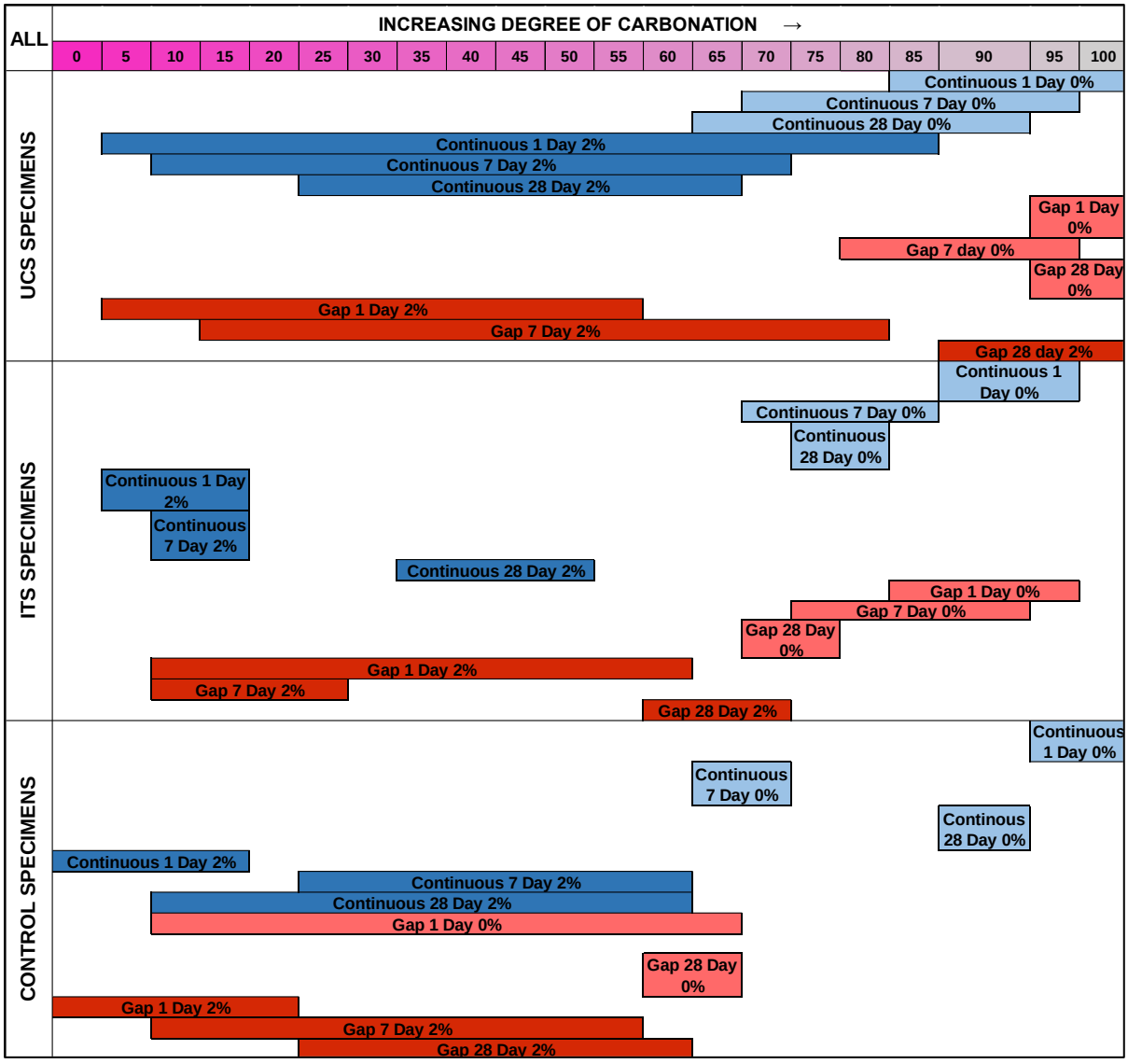


Figure 4-3: Range of the Degree of Carbonation Observed for Various Specimen Types, Material Grading, Cement Addition and Curing Time

Figure 4-3 illustrates that RCA material with no addition of cement carbonates more readily than RCA material containing 2% cement content. This is supported by literature (Rezagholilou and Nikraz, 2012), which suggests that low cement content base layers can be in more danger of early carbonation (particularly if reliant on this strength). For the case where no cement is added to the RCA material, the available cementitious product is due to the latent cement adhered to the coarse fraction of RCA. In addition, the adding of 2% cement to RCA shows more resistance to carbonation than the specimens with 0% added cement, this holds true for both material grading at various curing times.

Furthermore, these results can be misleading in the sense that there were a total of 6 UCS specimens for each variable (with the exception of the 0% Gap Grade which is represented

by 3 specimens) versus a total of 3 ITS specimens. This results in a wider range of degree of carbonation for the UCS specimens in comparison to that of the ITS specimens.

The reason for this is that at curing time, t, prior to collectively carbonating a UCS, ITS and a control specimen in each of the three carbonation chambers (Approach 2), an additional two UCS specimens of 0% and 2% cement addition were carbonated (Approach 1) together in a single chamber. Therefore, it is better fit to represent the data by observing the degree of carbonation of the specimens involved in each of these approaches separately and instead, use Figure 4-3 more for general overview and understanding. It is important to note that Table 4-1 represents the carbonation of specimens with equivalent TSA, whereas Table 4-2 and 4-3 represents the carbonation of specimens with varying TSA's.

Table 4-1 shows the degree of carbonation for the UCS Specimens with 0% and 2% cement content placed together in the selected carbonation chamber as indicated. The outliers within each group are circled as shown. These outliers occur in the same carbonation chambers which may well infer that the individual carbonation chamber environments have an influence on the degree of carbonation, irrespective of the amount of cement or grading in/of the material. It is therefore necessary that these chambers are first investigated i.t.o of their extrinsic factors (i.e. is it equal within chambers that look like apparent outliers), this is further evaluated in Section 4.2.2, before the intrinsic factors could be isolated.

Table 4-1: Observed Degree of Carbonation for UCS Specimens Carbonated Together

UCS Specimens Carbonated Together		Continuous Grade		Gap Grade	
Days Cured	Chamber Nr	0%	2%	0%	2%
1	1	95	20	-	45
	2	95	10	-	55
	3	95	65	-	5
7	1	85	65	95	15
	2	90	70	80	60
	3	80	10	95	15
28	1	65	45	98	90
	2	90	65	99	95
	3	85	65	99	95

Data from accelerated lab carbonation of three specimen types, namely UCS, ITS and the control sample, of the same cement content placed together in a chamber at the same curing

time is shown in Table 4-2 and Table 4-3 for the specimens with 0% and 2% addition of cement, respectively. On consulting the data presented in these tables, the effect of the individual carbonation chamber environments on the degree of carbonation of each of the specimens' hints at the same observation as depicted in Table 4-1, however the disparity as in Table 4-1 not as pronounced. This could be attributed to the fact that all these specimens contained the same cement content whereas the specimens previously consulted contained 0% and 2% cement content. This results in the degree of carbonation of the specimens containing the same cement content having less variation.

Table 4-2: Observed Degree of Carbonation for UCS, ITS and Permeability Specimens Carbonated Together (0% Cement)

0% Cement Specimens Carbonated Together		Continuous Grade			Gap Grade		
Days Cured	Chamber Nr	UCS	ITS	CONTR	UCS	ITS	CONTR
1	1	98	95	99	99	85	65
	2	95	95	95	99	95	10
	3	85	90	99	95	90	20
7	1	95	70	70	95	90	-
	2	95	85	65	95	85	-
	3	70	85	70	95	75	-
28	1	85	80	90	98	75	60
	2	80	80	90	95	70	60
	3	80	75	90	95	70	65

Table 4-2 shows that the degree of carbonation for RCA material with 0% added cement attains near-full carbonation for both material gradings. The continuous grade RCA material illustrates a slight decrease in the degree of carbonation with an increase in curing time (1 vs 28 days), in the case of the UCS and ITS specimens, to that of the control sample. A similar observation is made for the gap grade RCA material but only for the ITS specimens. The gap grade UCS specimens were near fully carbonated with only very tiny specs of material appearing fuchsia-pink as a result of the phenolphthalein.

Table 4-3: Observed Degree of Carbonation for UCS, ITS and Permeability Specimens Carbonated Together (2% Cement)

2% Cement Specimens Carbonated Together		Continuous Grade			Gap Grade		
Days Cured	Chamber Nr	UCS	ITS	CONTR	UCS	ITS	CONTR
1	1	10	15	15	10	10	10
	2	5	5	10	30	60	1
	3	85	10	1	10	45	20
7	1	25	10	25	70	10	10
	2	25	10	60	80	10	55
	3	50	15	55	65	25	15
28	1	50	35	40	98	60	25
	2	25	50	60	98	70	60
	3	50	50	10	95	60	55

Table 4-3 indicates that with increasing curing time (1 vs 28 days), the specimens seem to become more resistant to carbonation for both grading's and all specimen types. This is contrary to what was found in the case of the RCA material of 0% cement content.

Table 4-2 together with Table 4-3 compares well with the results shown in Table 4-1, in a general sense. The following observations are noted going forward:

- In terms of the influence of TSA on carbonation, no profound conclusions can be made from the above data;
- RCA material with no added cement, readily carbonates regardless of the curing time and grading of the material;
- RCA material with 2% added cement is inclined to be less resistant to carbonation as curing time is increased, with continuous grade RCA exhibiting a higher resistance to carbonation than gap grade RCA.

This discussion can be seen as evaluating the observed effects which intrinsic material factors, such as grading, cement content and curing time has on the materials readiness to carbonate. However as mentioned earlier it is important that we evaluate the possible deviance of the extrinsic factors, amongst other factors that might have had the apparent "yellow" outliers to behave differently and this is evaluated in Section 4.2.2 and 4.3.3.

4.1.2 Considering the Temperature Variable

The environmental parameters such as temperature, relative humidity, CO_2 concentration and gas pressure were measured with Vernier measurement tools (discussed in Chapter 3). The carbonation chambers were set up in a temperature control room of ±25°C. From the chamber data of all the accelerated carbonation tests, this was well reflected with temperature data measuring an average temperature of 23°C ± 1°C for both the vacuum phase and gas inlet phase of continuous grade material. For the case of the gap grade material an average temperature of 23°C ± 3°C was measured for the vacuum phase of the accelerated carbonation and 22°C ± 1°C for the gas inlet phase. From these results it can be justified that the temperature remained relatively constant throughout the accelerated carbonation of all specimens and the influence of temperature on the carbonation of various specimens can be neglected for now.

4.1.3 Considering the Variables of Gas Pressure and Carbon Dioxide Concentration

The data measurements of gas pressure (P) and CO_2 concentration (CO_2) would of course vary between a minimum and maximum as a result of the recycle process i.e. vacuum phase, then gas inlet and then repeat. The objective was to dispel as much gas as possible from the chamber during the vacuum phase, this was to ensure that as far as possible, only pure CO_2 gas was present during the gas inlet phase. The concentration of the CO_2 gas present during the gas inlet phase was limited by the allowable pressure within the chamber. All of these environmental parameters have a direct combined influence on the diffusion constant of carbonation. For the purpose of this section, the chamber data for the outliers shown in Table 4-1, Table 4-2, and Table 4-3 above are observed to show if they too are outliers relative to the variables of the other chambers.

When referring to Table 4-4, the average measured environmental variables are shown for the gas inlet phase only as this is the phase during which carbonation is encouraged. The average pressure between vacuum and gas inlet (P_{vacuum}/P_{inlet}) phase is shown to get a sense of the pressure gradient, which is equally important. The average Pressure, P, represents the pressure measured during the gas inlet phase and this was used to compute the partial pressure of CO_2 (PP_{CO2}). The CO_2 concentration (CO_2 [ppm]) represents the average concentration of CO_2 present during all of the three gas inlet phases.

Furthermore, these variables are used to compute an estimate of the number of moles, n, of CO_2 gas present in each chamber. This value was used to validate the readings of the Vernier CO_2 measurement tool. The ideal gas law together with the van der Waals equation was used to compute the moles of CO_2 gas with the volume of each chamber measured as

$10.22x10^{-3}$ m^3 (10.22 litres) and an average temperature of 22.5°C converted to the Kelvin temperature of 295.65.

From the results shown in the tables to follow it can be seen that theoretically, constant mols of CO_2 gas was maintained during the gas inlet phase of the accelerated carbonation procedure. This corresponds well with both the measured gas pressure data and the concentration of CO_2 gas.

The specimens observed as outliers previously, based on the degree of carbonation, are listed here below again (marked with a green arrow for comparison with Table 4-1) and evaluated if they were identified as outliers i.t.o extrinsic factors. The factors deemed as outliers i.t.o apparent extrinsic disparity is marked in red in Table 4-4. It is clear from this table that the extrinsic factors that seem to be outliers do not coincide with those that have been identified in Table 4-1. It must be noted here that the data shown in Table 4-4 below relates to the UCS specimens carbonated together, which consist of the same TSA but different cement content (previously described as Approach 1).

Table 4-4: Carbonation Chamber Data of the UCS Specimens Carbonated Together

0% UCS and 2% UCS specimens Carbonated Together							
Grading	Days Cured	Chamber Nr	P [kPa]	CO_2 [ppm]	CO_2 [moles = n]	P_{vacuum}/P_{inlet}	PP_{CO2}
Continuous Grade RCA	1	1	NO DATA AVAILABLE				
		2					
		3					
	7	1	120	99746	49,73	29,4	115,5
		2	120	100123	49,99	19,1	113,9
		3	119	99765	49,39	34,2	115,3
	28	1	117	99729	48,55	31,2	113,1
		2	122	100144	50,61	18,6	115,2
		3	117	99913	48,45	27,2	112,3
Gap Grade RCA	1	1	NO DATA AVAILABLE				
		2					
		3					
	7	1	104	87596	43,25	33,7	101,0
		2	117	100102	48,54	24,6	112,0
		3	121	100046	50,29	17,6	114,1
	28	1	120	100150	49,93	18,3	113,5
		2	119	99746	49,67	32,1	115,8
		3	119	99932	49,46	27,6	114,7

However, a second order approach was performed considering the 'pressure gradient' between gas inlet and vacuum (P_{vacuum}/P_{inlet}). Sun, (2010), discusses the influence which

partial pressure has on the rate of the carbonation reaction. It is accepted that a high concentration of CO_2 increases the diffusion rate of CO_2 into the material which leads to an increased carbonation rate. Furthermore, a high concentration of CO_2 induces a high reaction rate and produces an increased water content within the pores of the specimen. For this reason, the pressure gradient (P_{vacuum}/P_{inlet}) , was evaluated within the batch considered (as seen in red in the list below) and measured against the % carbonation within that same batch (Table 4-1). The green arrows are shown after to see if the highest pressure gradient would provide the highest percentage carbonation:

- Chamber 3 (**continuous**, 7 days) (highest $P_{vacuum/inlet,}$ lowest % carbonation) ↑ ↓
- Chamber 1 (**continuous**, 28 days) (highest $P_{vacuum/inlet,}$ lowest % carbonation) ↑ ↓
- Chamber 1 (**gap**, 28 days) (lowest $P_{vacuum/inlet,}$ lowest % carbonation) ↓ ↓

The continuous grade show that the highest pressure gradient provides the lowest percentage carbonation but the opposite is true for the Gap grade. Considering this, it seems that there is no pattern that would lead to consider that the extrinsic factors (within the range of variability here) have a significant effect on carbonation.

The same exercise was performed for the specimens that were carbonated together of varying TSA but the same cement content (Approach 2). The extrinsic results of these specimens are listed in Table 4-5 and Table 4-6 for the specimens with 0% added cement and 2% added cement, respectively. The green arrows indicates the outliers as identified in Table 4-2 and Table 4-3 previously, based on the degree of observed carbonation of the specimens.

Table 4-5: Carbonation Chamber Data of the UCS, ITS and Permeability Specimens Carbonated Together (0% Cement)

0% UCS ITS and Permeability specimens Carbonated Together							
Grading	Days Cured	Chamber Nr	P [kPa]	CO_2 [ppm]	CO_2 [moles = n]	P_{vacuum}/P_{inlet}	PP_{CO2}
Continuous Grade RCA	1	1	118	99795	49,00	28,9	113,8
		2	119	100122	49,65	18,9	113,1
		3	117	99663	48,54	33,6	113,3
	7	1	119	99899	49,35	28,4	114,5
		2	122	100179	50,80	19,0	115.8
		3	119	99819	49,43	32,7	115,3
	28	1	114	99662	47,37	13,2	105,3
		2	119	100109	49,58	11,7	109,1
		3	120	99721	50,00	16,2	112,9
Gap Grade RCA	1	1	117	99788	48,63	29,1	112,9
		2	121	100144	50,10	19,2	114,4
		3	0	20	0,00	-	-
	7	1	117	99564	48,49	30,0	112,7
		2	120	100052	50,07	18,0	113,7
		3	117	100090	48,71	25,3	112,5
	28	1	119	99835	49,40	27,4	114,5
		2	121	100153	50,35	18,3	114,5
		3	119	99773	49,59	32,5	115,6

Table 4-6: Carbonation Chamber Data of the UCS, ITS and Permeability Specimens Carbonated Together (2% Cement)

2% UCS ITS and Permeability specimens Carbonated Together							
Grading	Days Cured	Chamber Nr	P [kPa]	CO_2 [ppm]	CO_2 [moles = n]	P_{vacuum}/P_{inlet}	PP_{CO2}
Continuous Grade RCA	1	1	119	97760	49,67	29,9	115,5
		2	122	100138	50,54	19,5	115,3
		3	120	99724	49,95	35,6	116,8
	7	1	117	99762	48,61	29,5	112,9
		2	121	100130	50,47	19,5	115,2
		3	120	99789	49,83	35,7	116,5
	28	1	120	99693	49,75	26,1	115,1
		2	122	100128	50,55	17,8	114,7
		3	119	99753	49,64	30,2	115,4
Gap Grade RCA	1	1	115	99497	47,93	30,0	111,4
		2	118	100034	48,97	17,6	111,1
		3	117	100098	48,57	25,6	112,3
	7	1	119	99824	49,49	21,4	113,5
		2	113	100158	46,97	14,4	105,2
		3	119	99804	49,43	23,7	113,9
	28	1	51	61706	21,08	8,1	44,4
		2	91	62654	37,99	24,7	87,7
		3	93	28715	38,64	21,7	88,9

For various specimen types carbonated together with 0% added cement:

- Chamber 3 (**continuous**, 1 day) (highest $P_{grad,}$ lowest % carbonation) ↑ ↓
- Chamber 1 (**gap**, 1 day) (highest $P_{grad,}$ highest % carbonation) ↑ ↑

When considering the measured data above, the same is observed in that there is no pattern between the outliers. As before, the same outcome is not apparent for the case of chamber 1 which contained the gap grade UCS specimens which were cured for 1 day.

For various specimen types carbonated together with 2% added cement:

- Chamber 3 (**continuous**, 1 day) (highest $P_{grad,}$ highest % carbonation) ↑ ↑
- Chamber 3 (**continuous**, 7 days) (highest $P_{grad,}$ highest % carbonation)) ↑ ↑
- Chamber 2 (**gap**, 1 day) (highest $P_{grad,}$ lowest % carbonation) ↑ ↓
- Chamber 2 (**gap**, 28) (highest $P_{grad,}$ highest % carbonation) ↑ ↑

Here, however it is very clear that the 28 day gap has significant different extrinsic factors applied in comparison to the others and cognisance should be taken when evaluating the results further.

Having evaluated the rest of the chamber data in correlation with apparent outliers (identified through percentage carbonation) and the extrinsic application of the other chambers (apart from those marked in red), it seems acceptable that the specimens in the chambers are measured by equal measure (similar extrinsic factors and thus not a variable). Hence, measuring the values, in comparison to that of isolating now the intrinsic factors, against the strength test results are justified. It is also important that the original outliers, identified in Table 4-1 to Table 4-3, are not discarded as this could very well be due to intrinsic variables.

4.2 Results of Carbonated Specimens Compared to Non-Carbonated Specimens

The carbonation of the various RCA material specimens were classified in terms of the 'degree of carbonation', represented as a percentage from visual inspection (refer to Chapter 3 and Section 4-2) and the extrinsic factors, which were "normalised" (i.e. accepted as equivalent) in the previous subsection. The intrinsic (mix) factors having an effect on carbonation can now be evaluated further.

As the visual interpretation of the carbonation percentage could still lead to subjectivity, the influence of the variables on the UCS is rather evaluated (as a direct outcome measurable pending the percentage carbonation) and the effect of carbonation on the strength of the material is articulated. First, through inspection here, on how carbonation effects the UCS value (Section 4.2.1) and then the trends observed i.t.o the UCS (Section 4.3). Following in

the next chapter a statistical evaluation method is implemented, with the UCS as a measurable outcome. This will allow a more quantifiable approach to the influence of intrinsic factors.

4.2.1 Influence of Carbonation on the Unconfined Compressive Strength

The results of the Unconfined Compressive Strength (UCS) tests for the non-carbonated and carbonated specimens are presented in Figure 4-4.

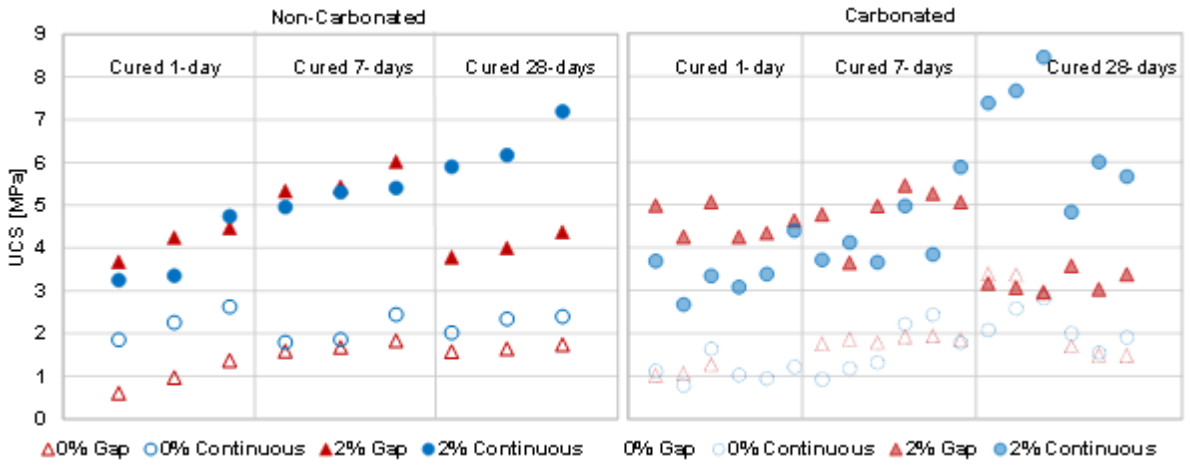


Figure 4-4: UCS Results for Non-Carbonated and Carbonated RCA Material

The results from Figure 4-4 show positive linear strength development over the curing periods of 1, 7 and 28 days for both non-carbonated and carbonated specimens. In the case of the non-carbonated UCS specimens, with 0% added cement, the gap grade specimens display slightly lower UCS strengths than the continuous grade specimens, irrespective of the curing periods. This can be attributed to the material structure which was described as being weaker for the gap grade specimens compared to that of the continuous grade specimens, specifically in this case where there is no cement present which is necessary to govern bonding strength. In the case of the carbonated specimens with 2% added cement, the UCS results conform well to each other for both grading types, implying overall a slight improvement of the gap grade UCS results of the non-carbonated specimens.

Observing the results of the specimens with 2% added cement, the UCS of the gap grade specimens are slightly higher than those of the continuous grade specimens, with the exception at curing time of 28 days. It must be noted that the UCS results of the gap grade material type for 28 days curing time are inconsistent (due to significant disparate extrinsic factors) as discussed earlier in this chapter. Isolating the data in terms of grading type and cement content (see Figure 4-5), the direct influence of carbonation on the UCS results is more evident.

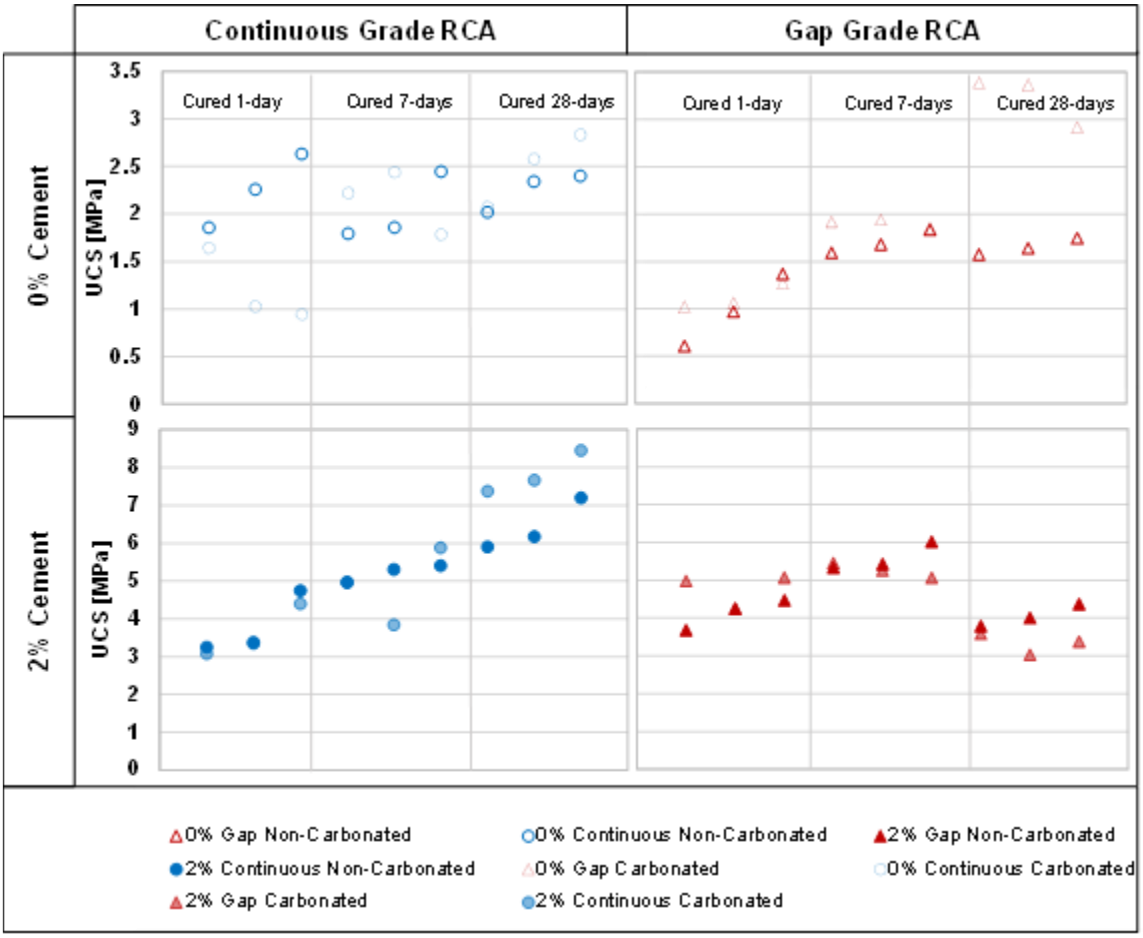


Figure 4-5: Effect of Carbonation on the UCS Results of two RCA Material Types (Continuous Grade and Gap Grade) with 0% and 2% Addition of Cement

Considering the UCS results of the continuous grade specimens with no added cement in Figure 4-5, specimens carbonated at a curing time of 1 day show a significant decrease in UCS results compared to non-carbonated specimens. At curing times of 7 and 28 days, however, the UCS results show a slight increase when the specimens are carbonated. In the case of the continuous grade specimens with 2% added cement, carbonation of the specimens show little influence on the UCS results at early curing times of 1 and 7 days. However, at 28 days curing time, carbonation of these specimens show to improve the UCS results. Therefore, this material (continuous grade RCA) shows higher sensitivity to carbonation at very early curing times (1 day) when 0% cement is added which seems to be able to be stunned when cement is added. On the other hand, at the curing time of 28 days, the UCS of continuous grade specimens (with 0% added cement) showed to improve when carbonated.

For reasons previously outlined, when considering the results of the gap grade materials, the specimens cured at 28 days are immediate outliers and the results hereof cannot be included

holistically. Nevertheless, focusing on the UCS results of the 1 and 7 day curing times of the gap grade specimens, generally, carbonation indicates a positive outcome.

The addition of cement plays a key role in the bonding strength within a material matrix but also provides cement hydration products which can be carbonated. Overall, the results seem to indicate that carbonation of a weak (based on poor structure, in this case gap grade specimens) cementitious material can improve the UCS of the material significantly. Some literature ostensibly supports this and even suggests treating RCA before constituting it as a material to improve the interfacial transition zone (ITZ) of the material. Improvement of the ITZ, encourages better packing of the material which has a positive influence on the mechanical properties.

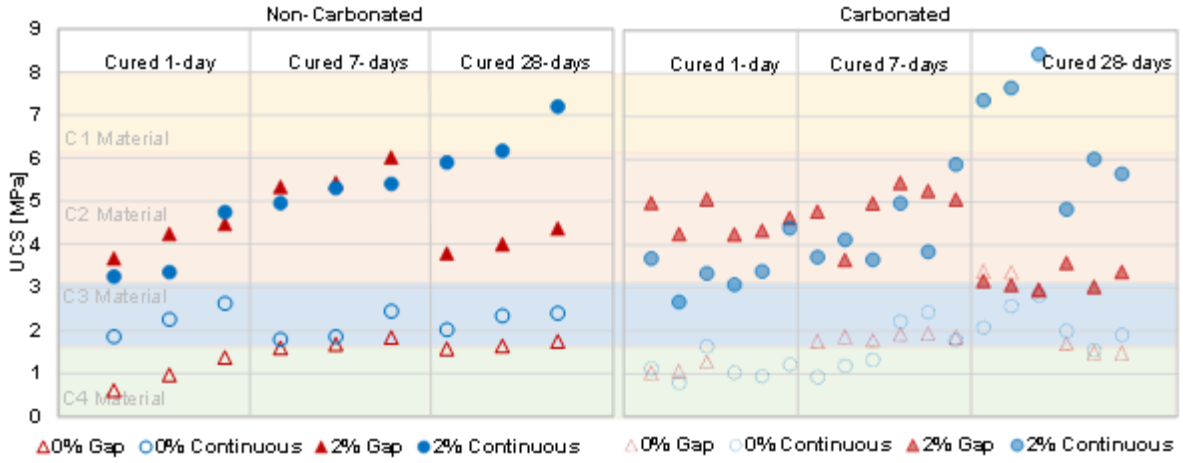


Figure 4-6: UCS Results for Non-Carbonated and Carbonated RCA Material in Relation to Typical Classes of Bound Material Layers

Another way to categorise the UCS results of these two RCA materials is by comparing them to typical categories of cement stabilised materials. With reference to Figure 4-6, majority of the UCS results, of both grading types and 0% cement added, fall within the requirements of a C3 and C4, with the latter being dominated by the carbonated specimens at earlier curing times. Through the addition of 2% cement, the material strengths fell predominantly within the requirements of a C2 stabilised material.

To gain better understanding of the degree of variation in strength development of the above mentioned materials, the data is displayed as a column chart. The columns represent the average UCS strength for each material type, cement content and curing time for both non-carbonated and carbonated specimens. The relevant standard deviation of each data set is represented by error bars (see Figure 4-7).

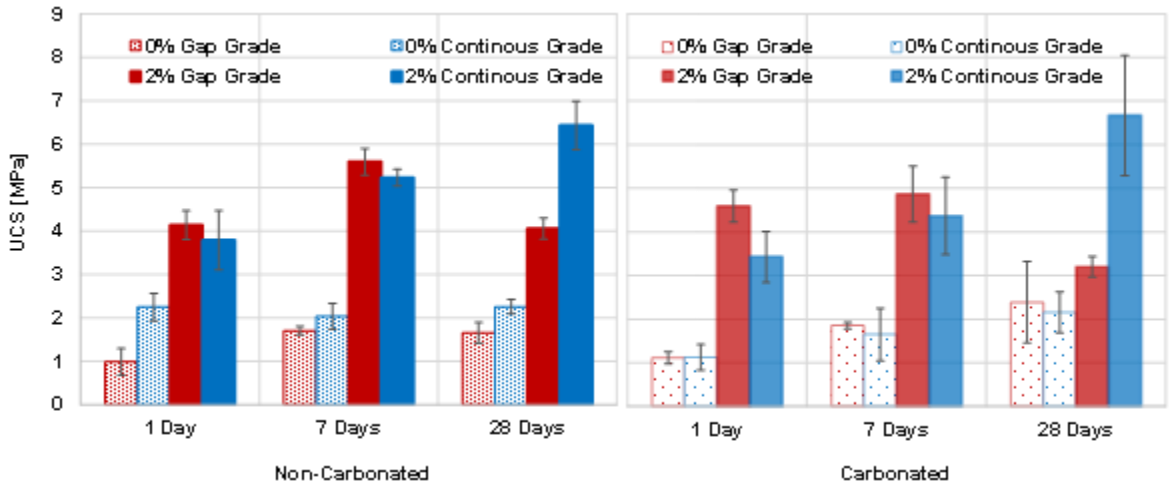


Figure 4-7: Influence of the Curing Time on UCS of Non-Carbonated and Carbonated RCA Specimens

Figure 4-7 depicts a general increase in strength development with increasing curing time. This trend is however not carried forward in the case of the gap material type at a curing time of 28 days, where a strong decrease in strength gain is observed. This deviation is most likely due to the influence of material properties such as density (or degree of compaction) and moisture content, this is discussed in further detail at a later stage.

The influence of accelerated carbonation on the strength development of RCA resulted in a mixed response. Based on the observed average UCS values, carbonation had the greatest positive response on the 0% gap grade material. For this case the UCS increased by 14%, 9% and 45% due to accelerated carbonation of the specimens at curing times of 1, 7, and 28 days, respectively.

The greatest negative response was of the 0% continuous grade material in which carbonation decreases the UCS results by 50%, 19% and 4% at 1, 7 and 28 days curing time, respectively. A summary of the percentage change in UCS, as a result of carbonation, is shown in Table 4-7 below.

Table 4-7: Percentage Change in UCS as a Result of Accelerated Carbonation at Various Curing Times for specimens with 0% and 2% Cement Added

Cement Added/ Days Cured	Continuous Grade		Gap Grade	
	0%	2%	0%	2%
1	-50%	-9%	14%	11%
7	-19%	-16%	9%	-13%
28	-4%	4%	45%	-21%

In general, the influence of carbonation on UCS improved with increased curing time when 0% cement was added. The green highlighted cells indicate observed outliers. The reason for these 'outliers' are not obvious by simply comparing UCS to curing time. For this reason the influence of material variables such as dry density and moisture content at time of testing and pH-value should be investigated and how this is connected to its UCS counterpart.

4.3 Results of UCS Specimens considering the separate variables

4.3.1 Dry Density

The dry density of a specimen indicates the structure of the matrix of the specimen, which ultimately influences the material strength. Therefore, an increase in density results in an increase in strength of the material.

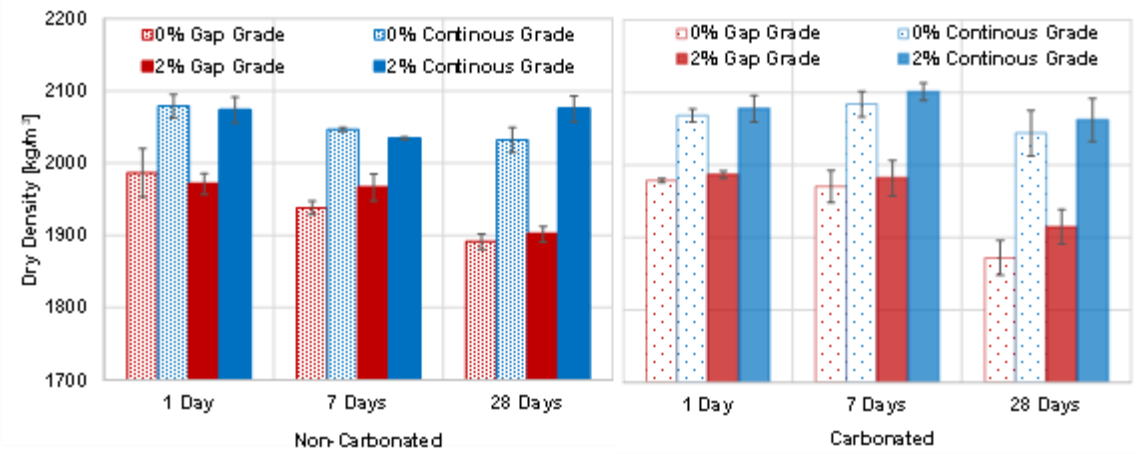


Figure 4-8: Dry Density at Testing of Continuous Grade and Gap Grade RCA Material

Figure 4-8 illustrates the densities of the various material types at time of testing. The target density of the gap grade and continuous grade material was 2050 kg/m^3 and 2150 kg/m^3, respectively. The density was not satisfied in the case of the 28 day gap grade material, and to a lesser extent, the 7 day non-carbonated gap grade and continuous grade material type. This explains the low UCS strengths achieved for these cases.

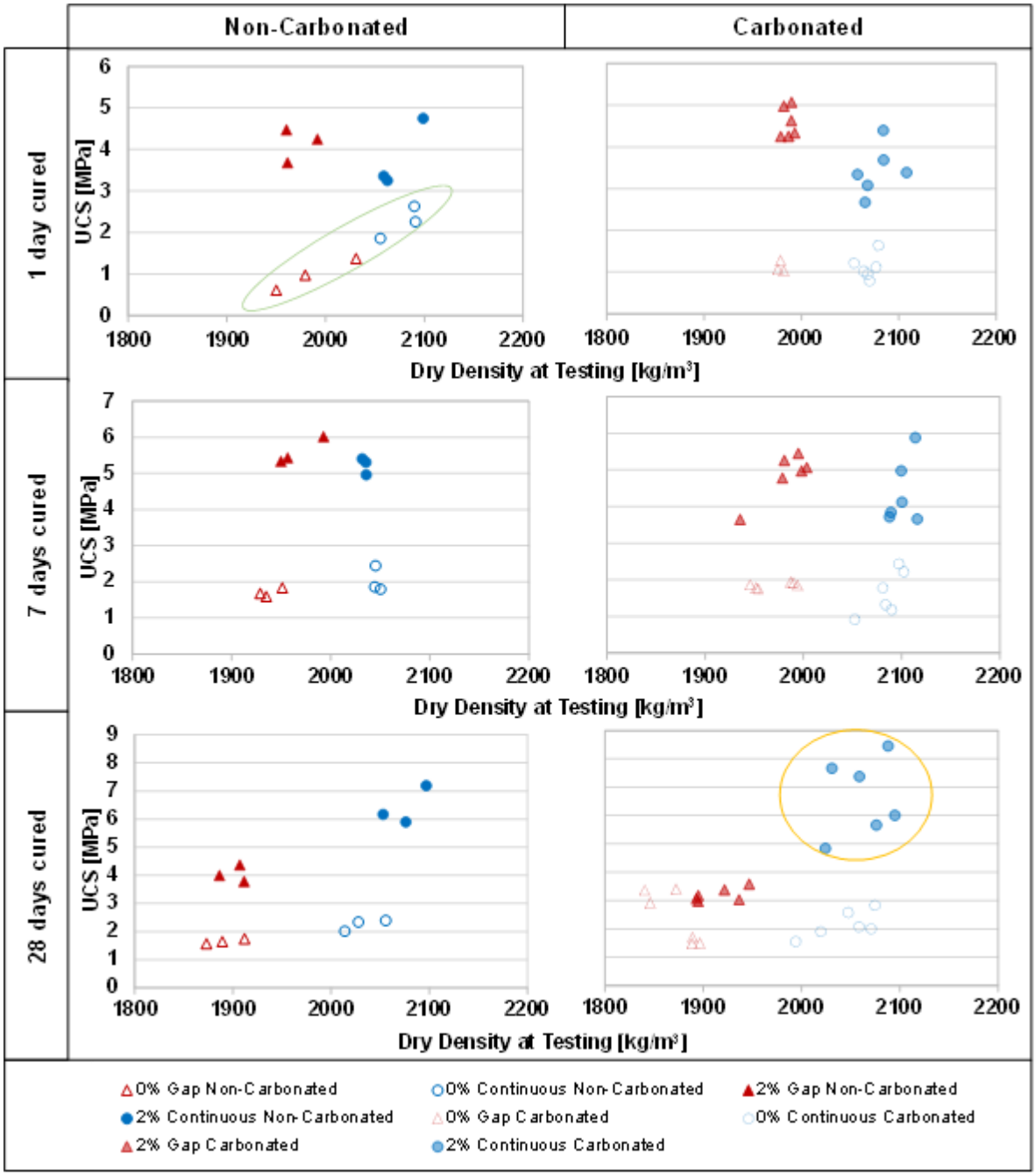


Figure 4-9: Relationship between Dry Density at Testing and UCS of Non-Carbonated and Carbonated RCA Specimens

Figure 4-9 represents the relationship between the UCS results and the corresponding DD_{test} of carbonated and non-carbonated specimens. In most cases, where a large enough difference between the dry densities of a set of specimens was present, a clear linear relationship can be seen in relation to the UCS result. For example, the non-carbonated specimens cured for 1 day with 0% added cement (Circled in green) show a linear increase.

It is also evident that there are hidden variables influencing the relationship between UCS and the DD_{test}. For example, a shift is evident in the UCS values of the carbonated continuous

grade RCA material cured for 28 days. Although the dry density of these specimens are very similar, their corresponding UCS results differ by ±2.5MPa (circled in orange). These variations are believed to be due to varying moisture contents.

Furthermore, if the above data is represented as a combined column chart (representing the UCS values) and scatter chart (representing the DD_{test}), there does not seem to be a clear trend showing the influence of DD_{test} on UCS. Figure 4-10 represents the results of the non-carbonated and carbonated continuous grade UCS specimens with 0% and 2% addition of cement. This data does not clearly indicate that an increase in DD_{test} results in an increased UCS result, particularly for the carbonated specimens. The same can be said for the case of the gap grade RCA specimens (refer to Figure 4-11)

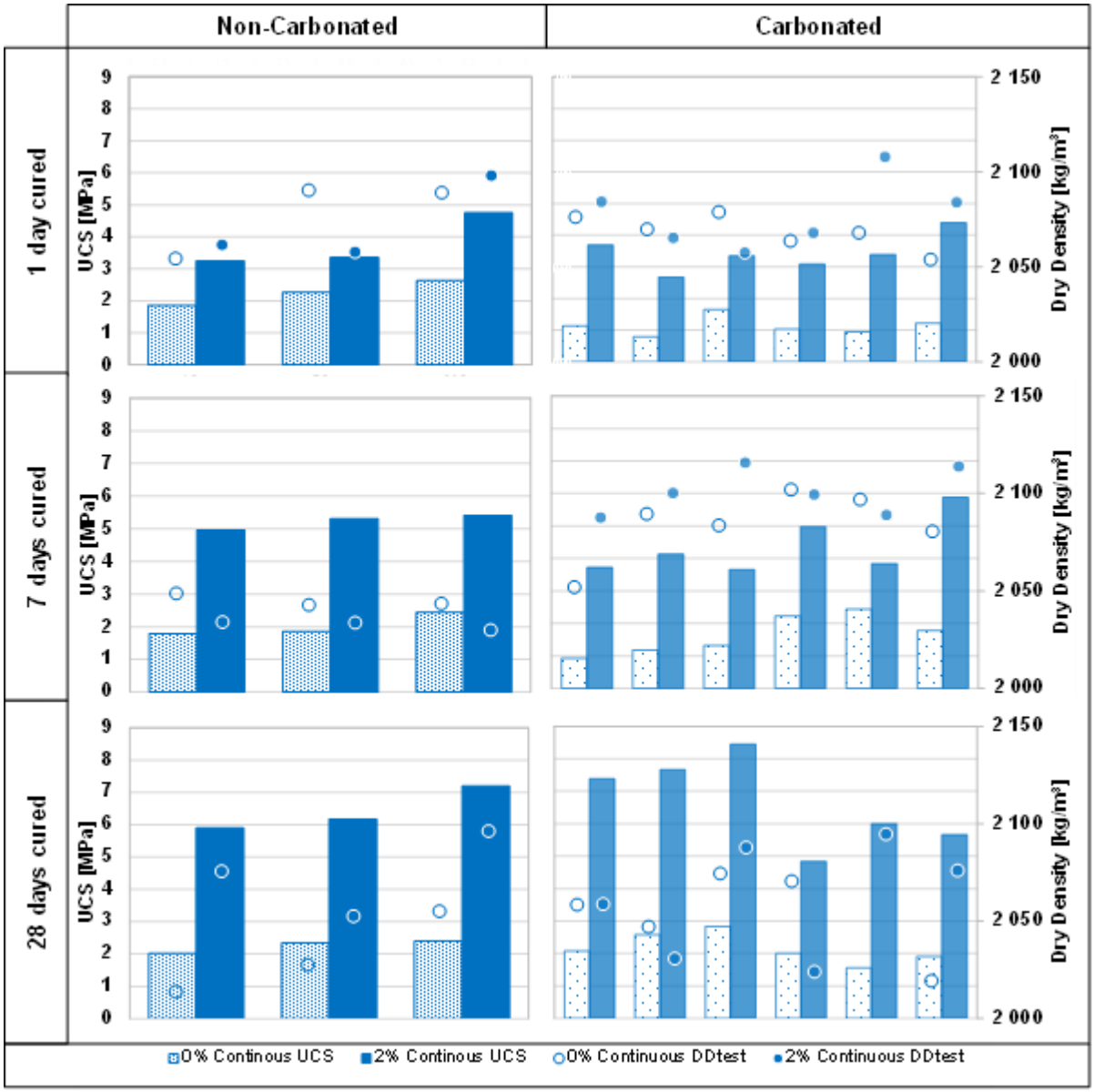


Figure 4-10: Graphical Presentation of the Influence of Dry Density on the UCS of Continuous Grade RCA Material

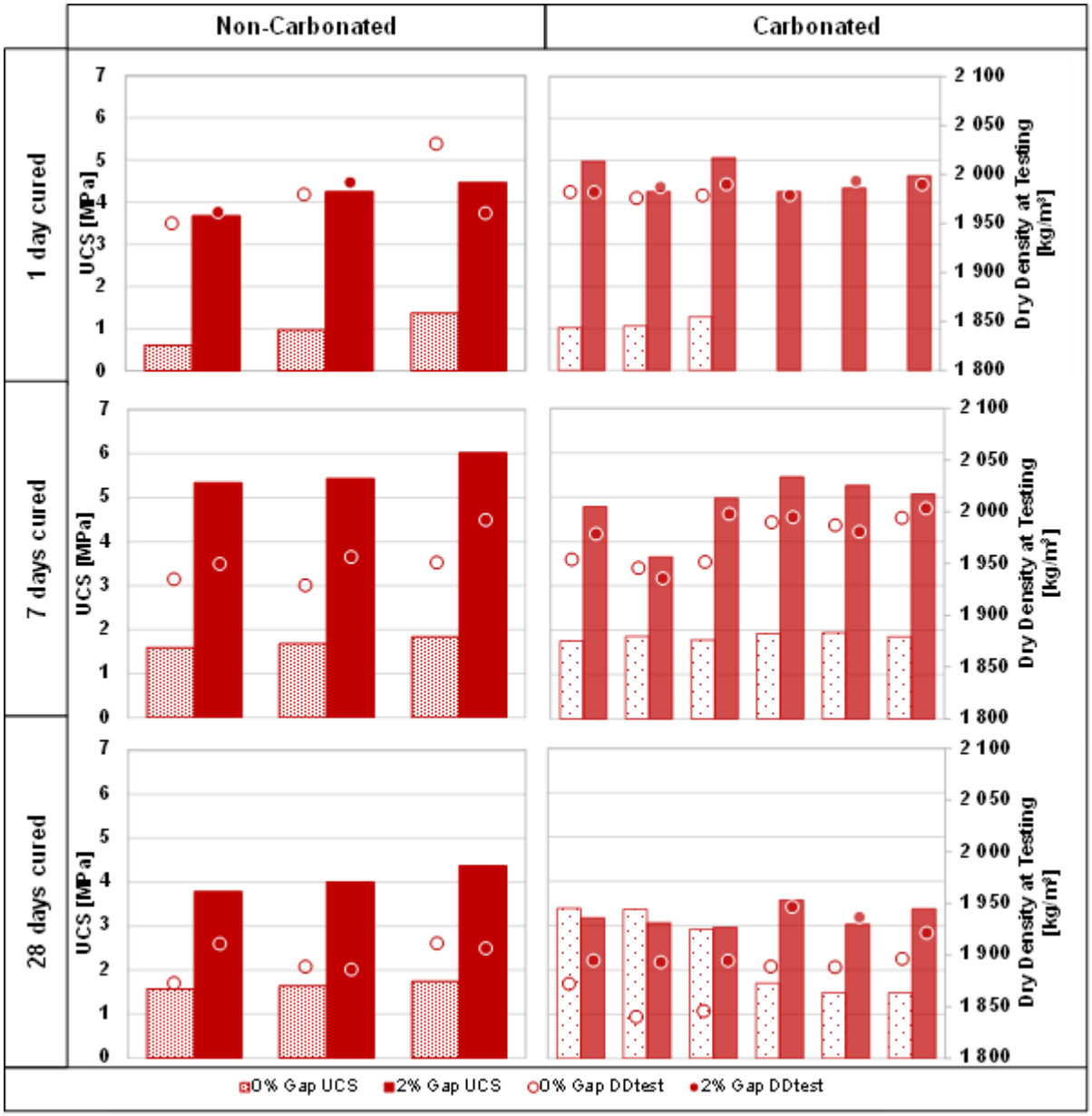


Figure 4-11: Graphical Presentation of the Influence of Dry Density on the UCS of Gap Grade RCA Material

In summary, there seems to be a trend in that the densities are correlated to the UCS, but in some cases suggest that other factors are at play.

4.3.2 Moisture Content

The moisture content at time of testing (MC_{test}) has a direct influence on the density of a material. For this reason it will have an effect on the outcome of the strength of a material.

Figure 4-12 presents the average MC_{test} of the UCS specimens which range between 9.3 and 11.5%. This range is as a result of the original moisture contents and the sensitivity of RCA to hygroscopic moisture as discussed previously in Chapter 3.

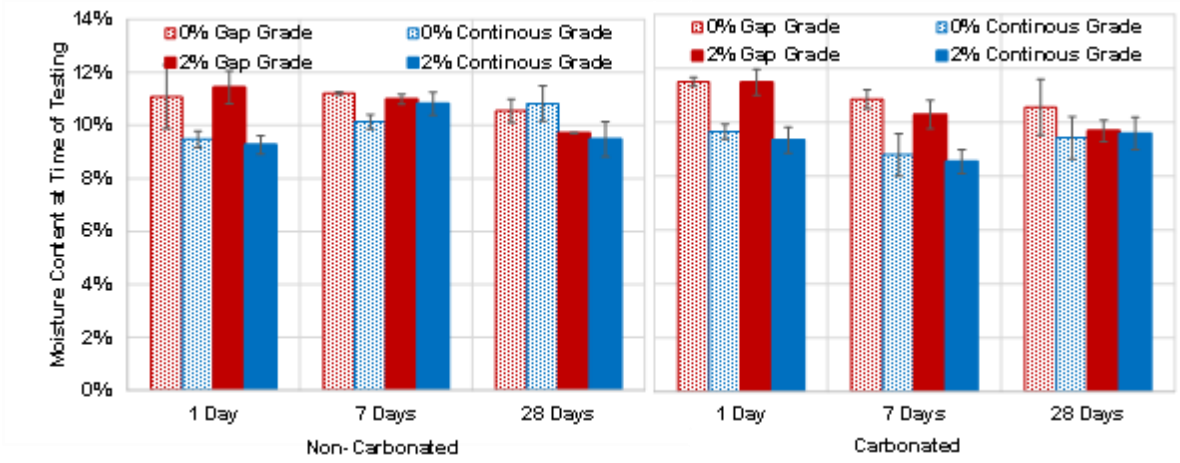


Figure 4-12: Average Moisture Content (%) of Non-Carbonated and Carbonated RCA Material

Figure 4-13 and

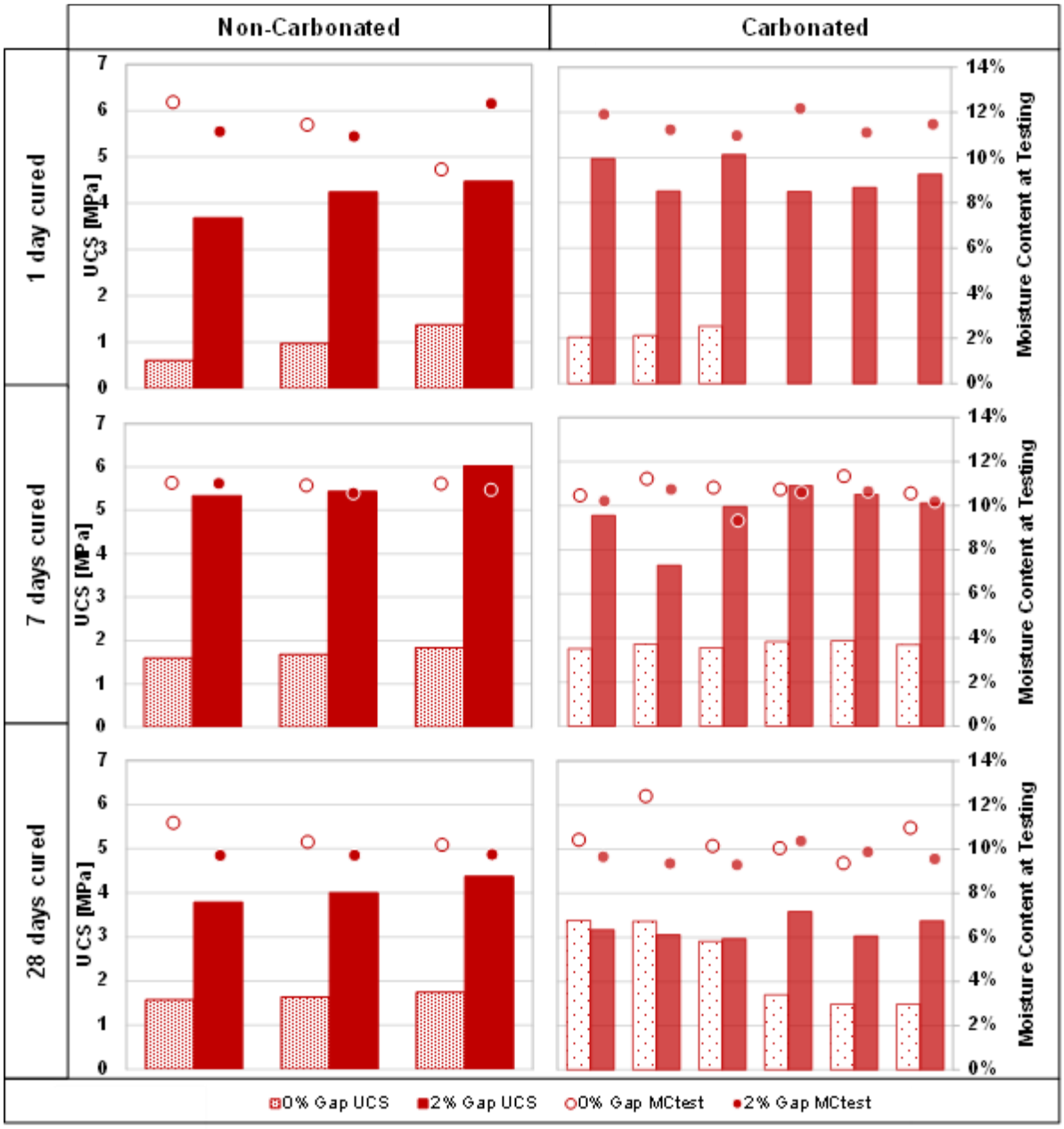


Figure 4-14 represent the MC_{test} of the various specimens against the UCS result. For the continuous grade material, the results indicate no apparent correlation between the MC_{test} and the UCS for the non-carbonated and carbonated material. Although it was expected that there would be a better correlation with the carbonated specimens, assuming that it has reverted to somewhat of a granular material form.

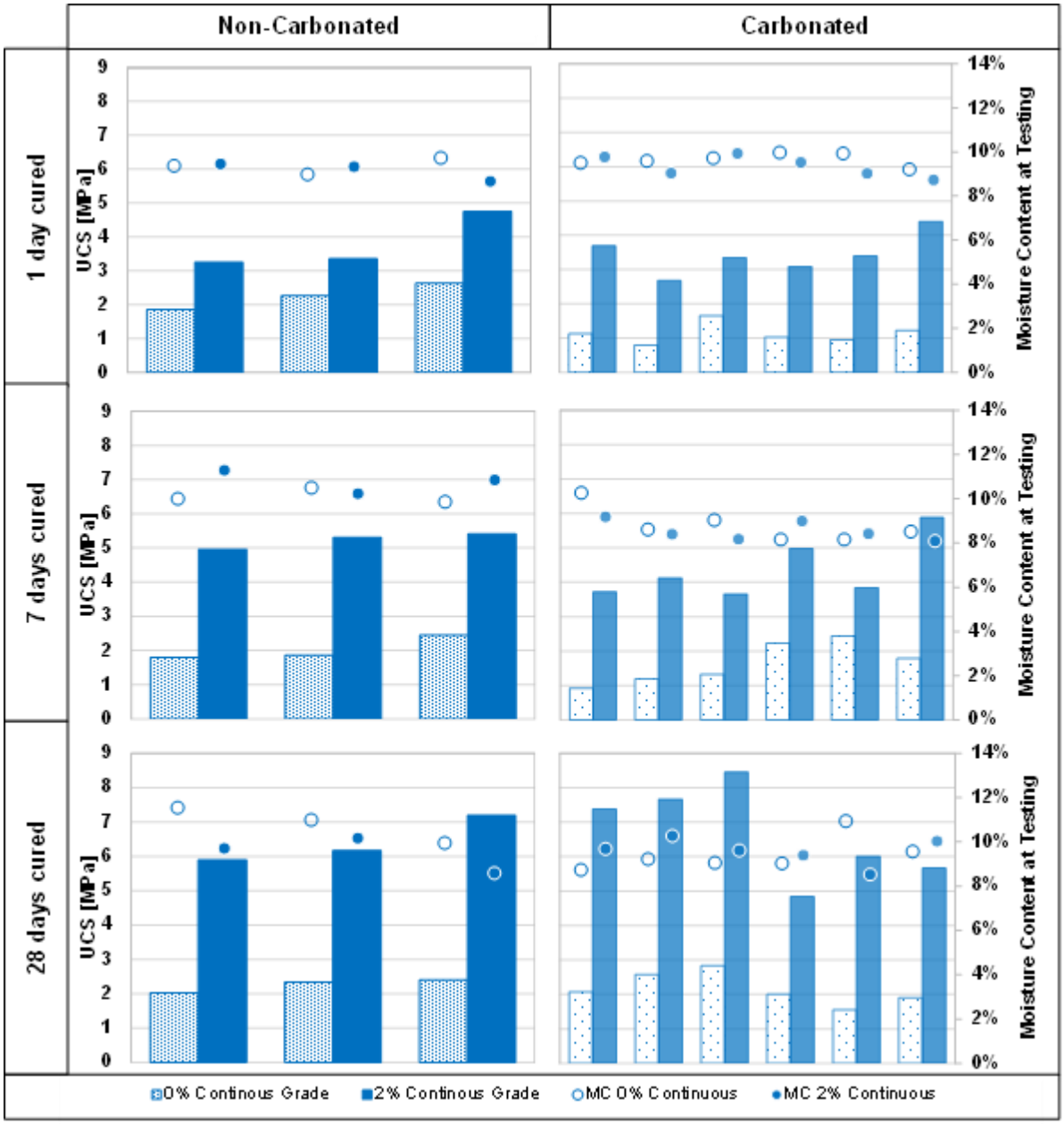


Figure 4-13: Relationship between the UCS and Moisture Content of Continuous Grade RCA Material for Non-Carbonated and Carbonated

In contrast to the continuous grade material, the results of the gap grade material (Figure 4-14) showed some inverse direct correlation with the UCS for non-carbonated material. Probably here, it could be that the bonds for cementing were lower due to lesser particles making contact as a result of the grading matrix. Yet, if these results in general are compared to that of the continuous grade material the UCS results are not lower in the non-carbonated form.

Again, no apparent correlation between the MC_{test} and the UCS can be seen through visual inspection of the graphs. In fact, it seems that most results are directly proportional (i.e. as moisture content increase so does the UCS). On first thought it seems counterintuitive,

however, one reason that can explain this phenomenon is the fact that with carbonation, the reaction involves the formation of $CaCO_3$ and expels water. As a result, the longer the carbonation reaction is sufficed, the more water will be formed within the material structure. Furthermore, $CaCO_3$ is denser than the initial CO_2 and $Ca(OH)_2$ reactants and with the result, formation of $CaCO_3$ could potentially lead to higher UCS. However, no tangible evidence can be supplied to substantiate this theory.

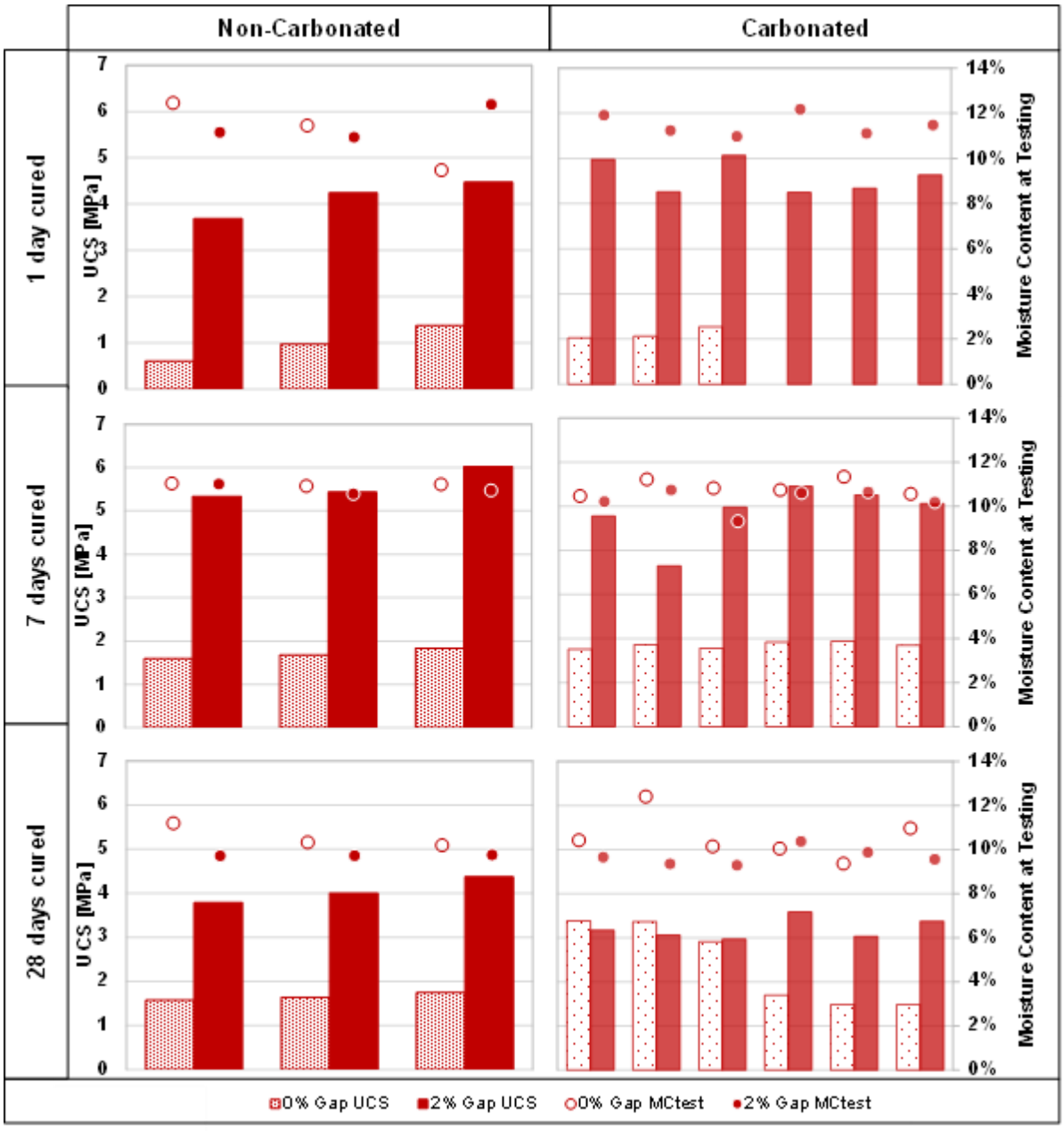


Figure 4-14: Relationship between the UCS and pH value of Gap Grade RCA Material for Non-Carbonated and Carbonated

4.3.3 pH-value

The pH is a scale used to measure the alkalinity of a material. From

Figure 4-15 and Figure 4-16, below, it is evident that carbonation shifts the pH value of a material to a more alkaline (lower pH) level.

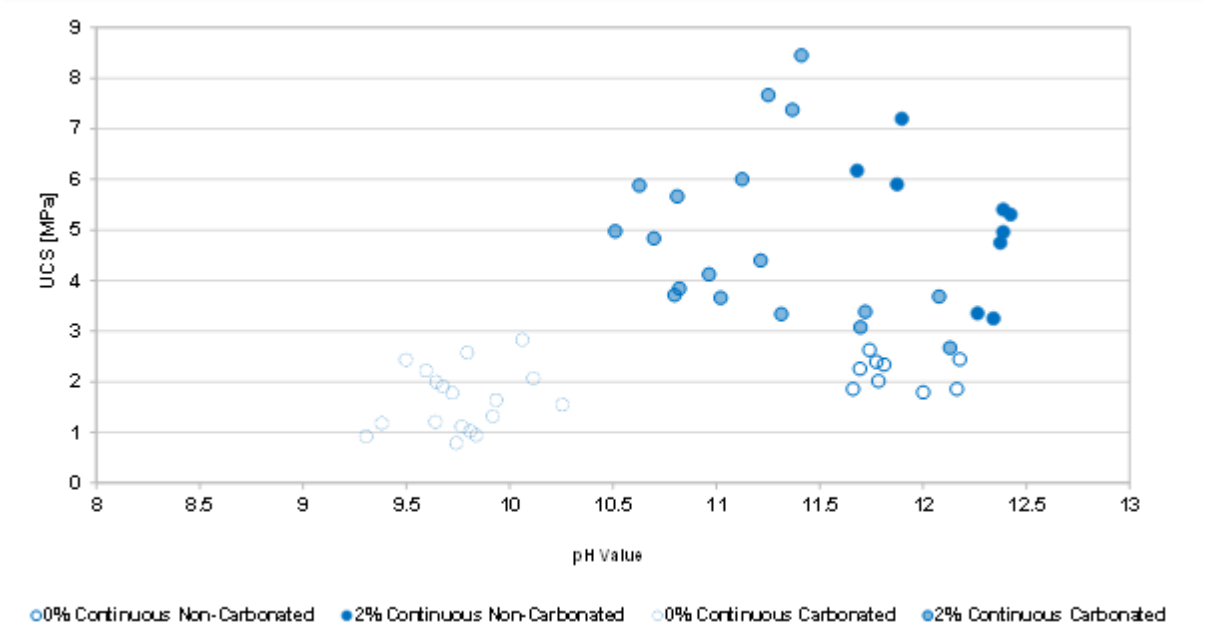


Figure 4-15: Relationship between the UCS and pH value of Continuous Grade RCA Material for Non-Carbonated and Carbonated

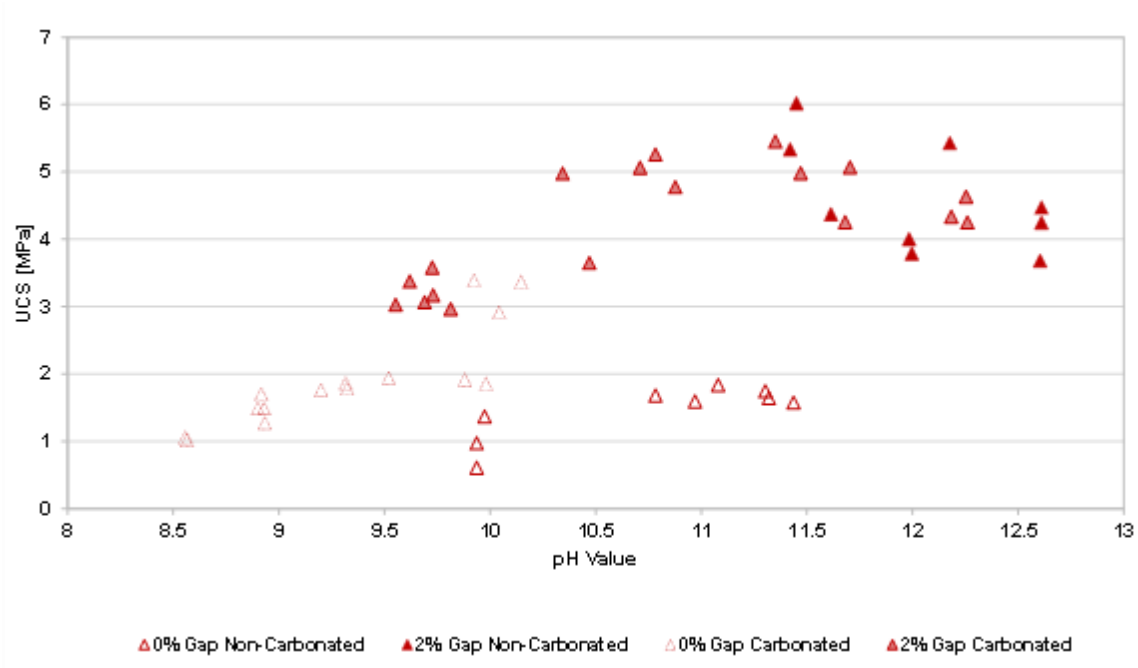


Figure 4-16: Relationship between the UCS and pH value of Gap Grade RCA Material for Non-Carbonated and Carbonated

It is well known that the addition of cement increases the material's pH-value, this is supported by Figure 4-15 and Figure 4-16. Literature also shows that one of the durability issues of

cement stabilised materials, is the material's ability to maintain a specific pH-value over time, this ensures the stability of cementitious products. Carbonation has been identified as one of the major causes for loss of a material's pH (or alkalinity), with reference to Figure 4-15 and Figure 4-16, it is clear to see that carbonation does indeed lower the pH-value of RCA material.

What has not been considered in the above graphs is the influence of curing time. Over time, the chemical reactions within a material mix eventually stabilise. However, within the first few days, these reactions are more vigorous and could result in misleading pH-values. Figure 4-17 illustrates the pH-values of these materials at various curing times. In the case where 0% cement was added to the materials, both the gap grade and continuous grade specimens show stable pH values with a slight increase in some cases. The opposite is observed in the case of specimens with 2% added cement which demonstrate varying pH-values at the different curing times.

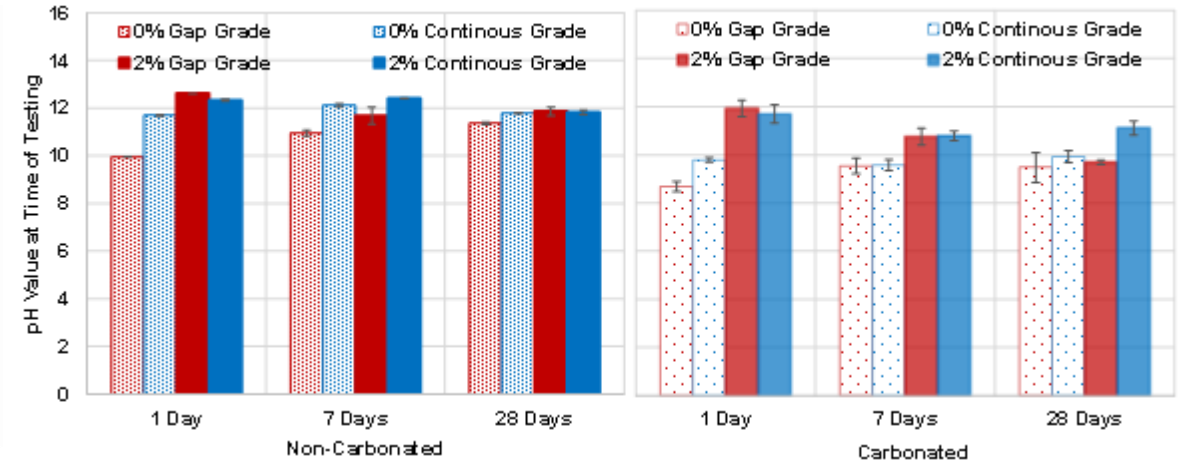


Figure 4-17: pH Value of RCA Material at Various Curing times for Carbonated and Non-Carbonated Specimens

The percentage decrease in pH-values, as a result of carbonation, is summarised in Table 4-8 for continuous and gap grade specimens at the relevant curing times and cement contents.

Table 4-8: Percentage Decrease in pH-value as a Result of Accelerated Carbonation at Various Curing Times for 0% and 2% Added Cement

Cement Added/ Days Cured	Continuous Grade		Gap Grade	
	0%	2%	0%	2%
1	16	5	13	5
7	21	13	13	8
28	16	6	17	18

It is evident that the above mentioned variables, namely density, moisture content and pH-value, all influence the UCS of continuous grade and gap grade RCA specimens. What is more important is how these variables influence the UCS in relation to one another and an example of the pH-value as the related variable is shown in Figure 4-18 and Figure 4-19, for continuous grade and gap grade RCA, respectively.

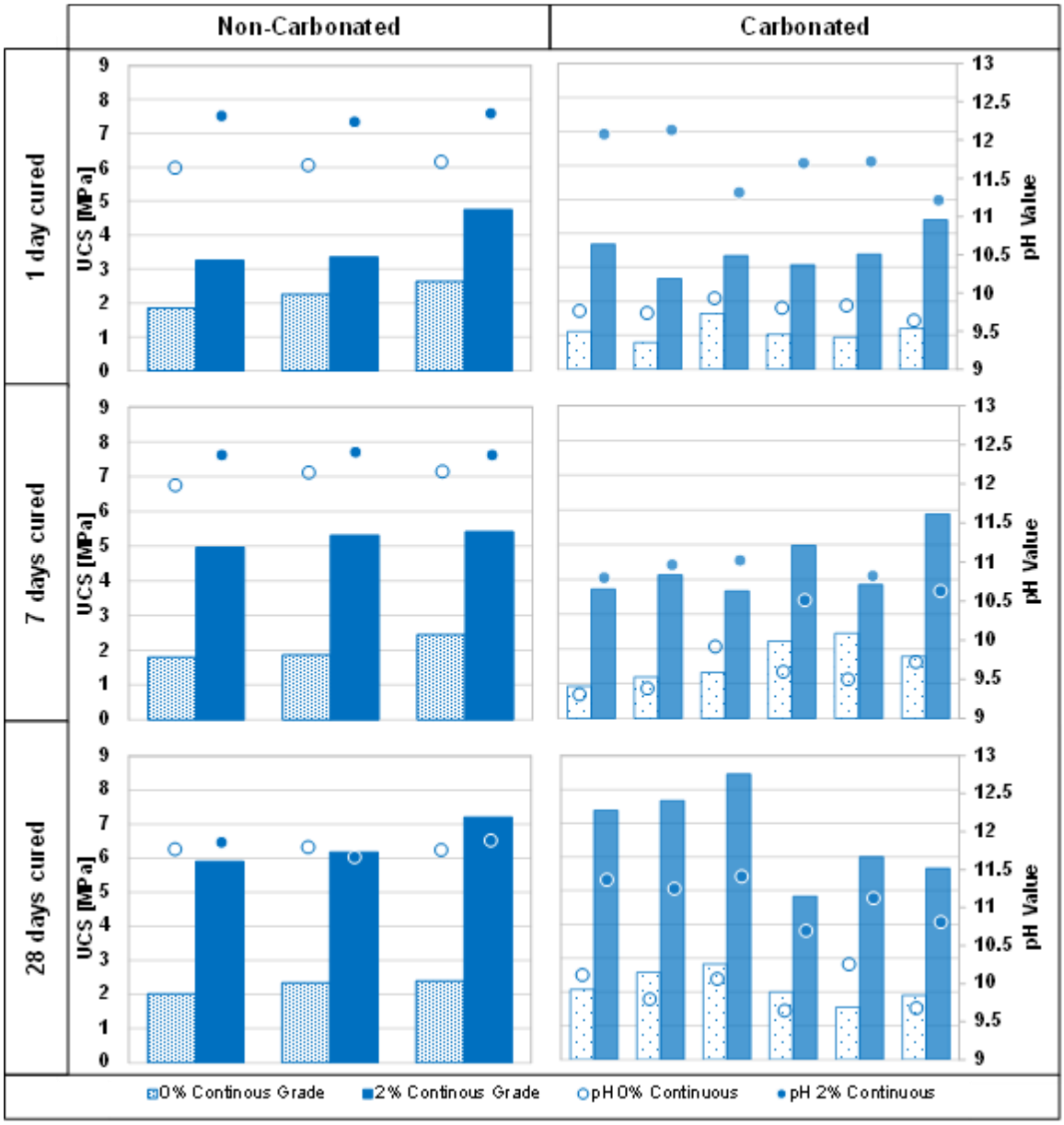


Figure 4-18: The UCS of Non-carbonated and Carbonated Continuous Grade RCA in Relation to the pH-Value of the Material

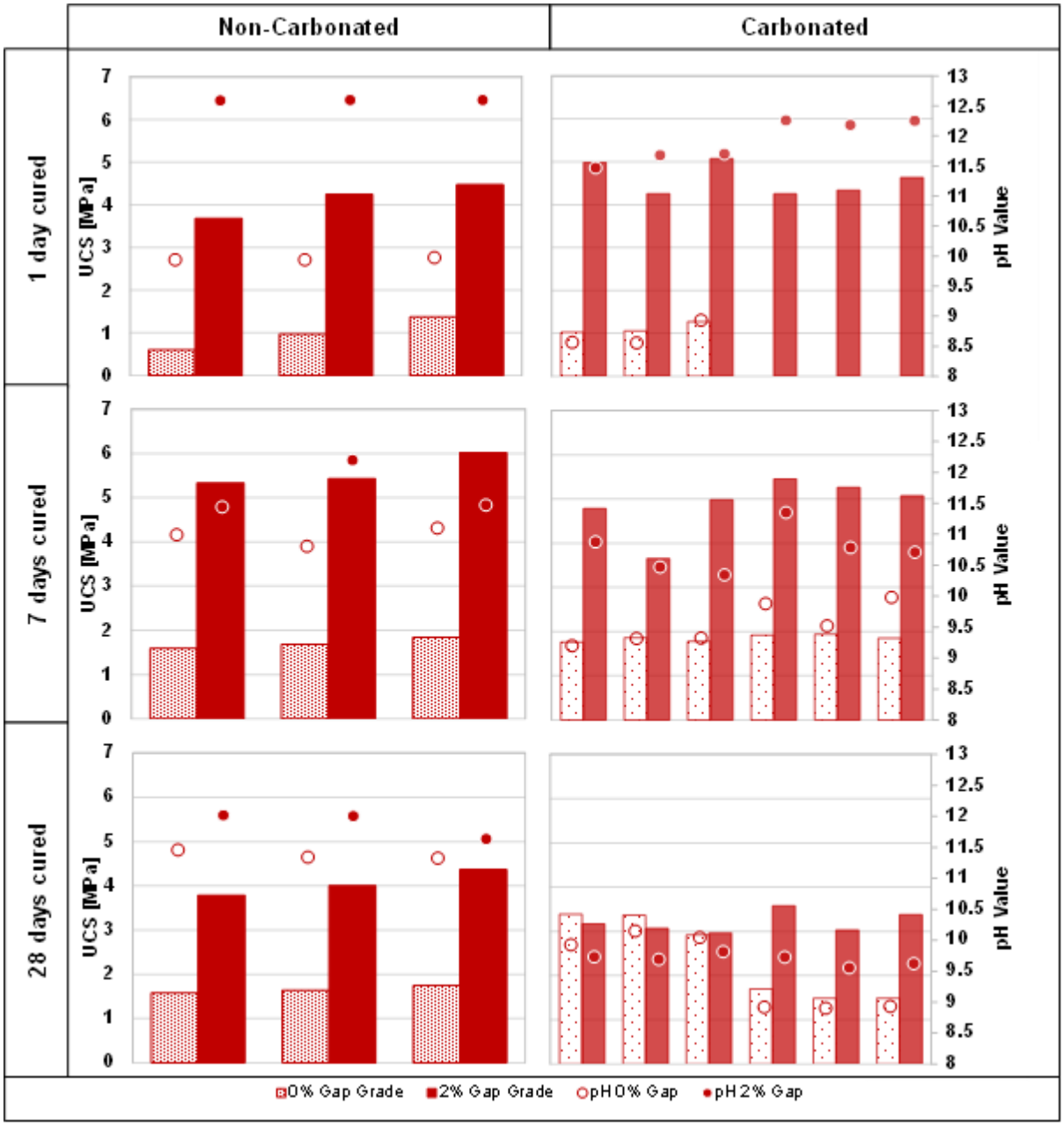


Figure 4-19: The UCS of Non-carbonated and Carbonated Gap Grade RCA in Relation to the pH-Value of the Material

Through inspection of the results above, the pH-value in relation to the UCS result rendered the identification of much generalised results with some stochastic counterintuitive outcomes. It is therefore necessary that a more statistical approach was taken to clarify the influence of variables on the UCS outcome. This is performed in the next section.

4.4 Analysis of Variance and Reliability of UCS Data

UCS of a material is dependent on a number of factors, such as, density, moisture, curing time, cement content, material grading etc. In addition, this holds true for the carbonation of materials and therefore it was found suitable to incorporate multivariate analysis. Multivariate analysis simultaneously analyses two or more independent (predictor) variables that influence the outcome of the dependent variable under investigation. For the purpose of this section, the independent variables include cement content, moisture content at testing, dry density at testing and pH value; and the independent variable represents the UCS of the material. A type of multivariate analysis is a statistical technique known as multiple regression. This technique predicts the dependent variable based on multiple independent variables.

The multiple regression analysis was performed using Microsoft Excel. It is important to note that Excel outputs coefficients of a linear equation. If non-linear equations are required, the input data is required to be converted as such before input.

Through Analysis of Variance (ANOVA) it was possible to identify the significance of the influence of selected variables on the UCS of continuous grade and gap grade RCA specimens. ANOVA is a statistical method used to determine if the data presented consists of equal means. The hypothesis for analysis is always a one-tailed test. For the following data, the null hypothesis, H_0, tested is that there is no relationship between the independent variable and dependent variables. The alternate hypothesis, H_A, is that a relationship does exist between the independent variable and dependent variables. The null hypothesis is rejected when the p-value is shown to be less than the level of significance, $\alpha = 0.05$ (refer to Table 4-9).

Table 4-9: Stating the Hypothesis of the Data Analysis

Hypothesis	State Hypothesis	Reject Hypothesis
Null Hypothesis: H_0	No relationship exists between independent variables and dependent variable	p-value < 0.05
Alternative Hypothesis: H_A	A relationship does exist between independent variables and dependent variable	-

As stated, the UCS result was considered the independent variable with cement content, moisture content, dry density and pH-value of the material representing the independent variables.

Table 4-10 and Table 4-11 represent the summarised results obtained from the statistical analysis performed on the non-carbonated and carbonated RCA material, respectively. Furthermore, the analysis was performed for continuous grade and gap grade RCA material for curing times of 1, 7, and 28 days. The highlighted cells indicate positive outcomes.

Table 4-10: Summary of the Results Obtained from the Statistical Analysis of Non-Carbonated UCS Specimens

Influence of Material Properties on Performance (UCS): Non-Carbonated Specimens					
Material Type	**Independent Variable**	**t stat**	**P-value**	**Significance F**	**R squared**
Continuous Grade RCA 1 Day Cured NonCarbonated	Cement Content	-0,016	0,990	0,340	0,947
	Moisture at Testing	-0,242	0,849		
	Dry Density	0,721	0,602		
	pH	0,264	0,836		
Continuous Grade RCA 7 Day Cured NonCarbonated	Cement Content	3,750	0,166	0,105	0,995
	Moisture at Testing	-1,455	0,383		
	Dry Density	-0,937	0,521		
	pH	0,056	0,965		
Continuous Grade RCA 28 Day Cured NonCarbonated	Cement Content	96,851	0,007	0,007	1,000
	Moisture at Testing	-31,890	0,020		
	Dry Density	-27,359	0,023		
	pH	19,175	0,033		
Gap Grade RCA 1 Day Cured NonCarbonated	Cement Content	-0,769	0,583	0,091	0,996
	Moisture at Testing	0,684	0,618		
	Dry Density	0,141	0,911		
	pH	0,844	0,554		
Gap Grade RCA 7 Day Cured NonCarbonated	Cement Content	56,289	0,011	0,011	1,000
	Moisture at Testing	-3,569	0,174		
	Dry Density	11,593	0,055		
	pH	-3,869	0,161		
Gap Grade RCA 28 Day Cured NonCarbonated	Cement Content	9,649	0,066	0,067	0,998
	Moisture at Testing	-0,247	0,846		
	Dry Density	-0,571	0,670		
	pH	-3,011	0,204		

The results from Table 4-10 generally show good correlations, but care should be when considering these results in isolation. In contrast, the variables do not show positive support for rejecting H_0, except for the continuous grade RCA cured for 28 days. In other words, the ideal situation, which would indicate significance, implies that $p < 0.05$. Although this is the accepted 'norm', even significance up to the value of 0.3 would be acceptable as this would imply a 70% chance that the specific variable in question would be significant. One can see from these results that this is still not always the case and varies with curing time.

What is also of interest is that the significance of the p-value for cases seem to improve for the carbonated specimens (refer to Table 4-11) as opposed to the non-carbonated specimens. The results in Table 4-11 indicate that cement content and pH-value seem to be the most

significant influence on the UCS of carbonated RCA material for both material grading type with the exception of the continuous grade RCA cured for 28 days.

Table 4-11: Summary of the Results Obtained from the Statistical Analysis of Carbonated UCS Specimens

Influence of Material Properties on Performance (UCS): Carbonated Specimens					
Material Type	**Independent Variable**	**t stat**	**P-value**	**Significance F**	**R squared**
Continuous Grade RCA 1 Day Cured NonCarbonated	Cement Content	3,884	0,006	0,000	0,932
	Moisture at Testing	-0,018	0,986		
	Dry Density	1,492	0,179		
	pH	-1,793	0,116		
Continuous Grade RCA 7 Day Cured NonCarbonated	Cement Content	3,440	0,011	0,001	0,906
	Moisture at Testing	-0,514	0,623		
	Dry Density	0,749	0,478		
	pH	-1,856	0,106		
Continuous Grade RCA 28 Day Cured NonCarbonated	Cement Content	1,258	0,249	0,000	0,930
	Moisture at Testing	0,506	0,628		
	Dry Density	1,126	0,297		
	pH	2,051	0,079		
Gap Grade RCA 1 Day Cured NonCarbonated	Cement Content	3,318	0,029	0,001	0,978
	Moisture at Testing	0,455	0,673		
	Dry Density	0,515	0,634		
	pH	-1,098	0,334		
Gap Grade RCA 7 Day Cured NonCarbonated	Cement Content	4,031	0,005	0,000	0,966
	Moisture at Testing	0,420	0,687		
	Dry Density	1,889	0,101		
	pH	0,000	1,000		
Gap Grade RCA 28 Day Cured NonCarbonated	Cement Content	0,039	0,970	0,000	0,954
	Moisture at Testing	0,239	0,818		
	Dry Density	2,492	0,041		
	pH	7,236	0,000		

The results are further depicted in graph form in Figure 4-20 for ease of viewing. It is unfortunate but it seems that the significance, as analysed through a linear independent analysis, seems to show erratic variability in the significance of variables. Many of these variables show correlation in terms of the R-squared value, however, this significance does not hold true within the model. In some cases, the pH and cement content seem to show some strong correlation within the model and these are therefore considered as the most prominent variables for the purpose of this exercise.

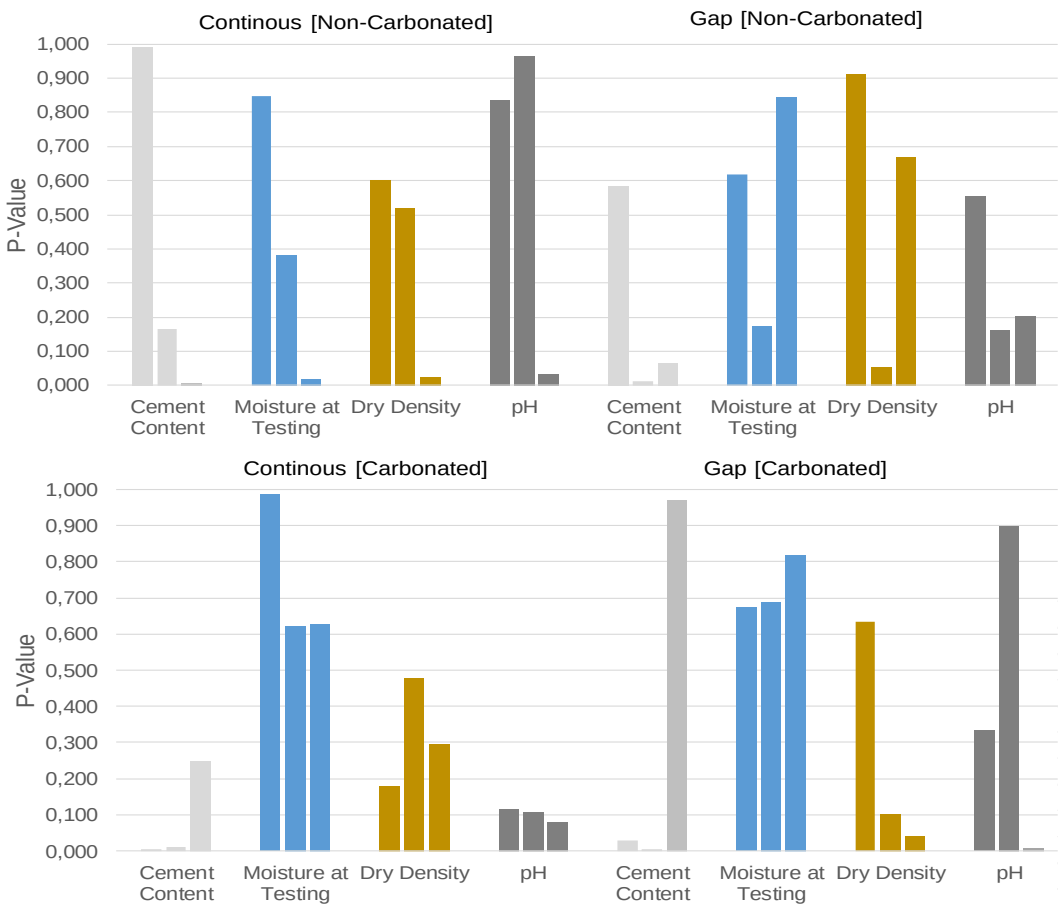


Figure 4-20: The Significance of Various Independent Variables on the Dependent Variable, UCS, for Non-carbonated and Carbonated Continuous and Gap Grade RCA Material

Through inspection, it was concluded that these results may not be a consequence of the dependency of the variables but rather the analysis method employed in this chapter. The current ANOVA does not allow for the examination of interdependency between variables, moreover, the variables in question are still in linear form. Nonetheless, there is an indication that the influence of the variables differ at varying curing times and this is evaluated in greater detail in the next chapter.

4.5 Conclusion

The outcome of these results indicate general trends of those variables which influence carbonation (mainly the cement content) and in particular, the resistance to carbonation of RCA material showed good correlation for both grading types.

RCA material, with 0% added cement, readily carbonates almost regardless of the curing time and grading of the material. In contrast, RCA material with 2% added cement is inclined to be less resistant to carbonation as curing time is increased, with continuous grade RCA exhibiting a higher resistance to carbonation than gap grade RCA.

However, it is evident that the data concerning the variables i.t.o of the visual interpretation are independent from each other and rendered stochastic results with some unexpected outcomes. Thus, although important trends were identified, it is clear that a more probabilistic/mathematical approach would be needed to articulate how the intrinsic variables interact and ultimately how these variables influence the results.

CHAPTER 5: MODELLING OF RESULTS

The previous chapter considered the analysis of the results, however, these results were limited as the variables were selected as independent from one another and furthermore, considered as linear. As an alternative approach, both interdependency and non-linearity of the same variables were considered. Furthermore, formulations found in literature were investigated and considered to improve the description of the behaviour of these variables, as outlined in the previous chapter.

Primarily, the formulations included interdependency of the selected variables for the results as a whole. Thereafter, the curing time of the specimens was isolated as an additional variable. Subsequent to the development of coefficients, using the latter approach, correlations were developed between that of UCS and ITS. This correlation made it possible to determine to what extent certain variables would have on both the UCS and ITS (and the change from carbonated to non-carbonated). Consequently, the influence which carbonation may have on pavement life was evaluated, as there is a direct relation between ITS and fatigue.

5.1 Modelling UCS Data

Many prediction models of UCS exist, some of which are listed below in Table 5-1. These models confirm that there is strong evidence that a relationship occurs between intrinsic variables and the UCS of pavement materials.

Table 5-1: Relationship between UCS and variables (Adapted from Xuan (2012))

Material	Prediction models of UCS	Reference	Remarks
CTG,M	$UCS = A \times C$	(Sherwood, 1968)	C= cement by mass;
	$UCS = K \times D^n$	(Sherwood, 1995)	D=density
	$UCS = 5.03 \times 10^4 [\frac{\eta}{(C_v)^{0.28}}]^{-3.32}$	(Consoli, Foppa, Festugato, & Heineck, 2007)	C_v=cement by volume η=porosity
	$UCS(t) = UCS(t_0) + k \cdot \log(t/t_0)$	(Terrel, et al., 1979a)	t=curing time
	$UCS(t) = UCS(28)\frac{t}{a + b \cdot t}$	(Lim & Zollinger, 2003)	

However, these models only include single variables, with no relation to interdependency. Xuan (2012) acquired the development of these estimation models for UCS and further related them to mixture variables. He based his formulation on the TRH13 (1986) as well as wotk done by Terrel *et al.* (1979), which revealed that the UCS increases linearly with the ratio of

cement (C) to water content (W) and exponentially with the dry density (D). This relationship is expressed by following equation:

$$UCS = a\frac{C}{W} * \left(\frac{D}{1000}\right)^8 \quad (5\text{-}1)$$

Where,

a = coefficient depending on the Recycled Masonry Aggregate (RMA) content

C = cement content by mass of aggregate [%]

W = water content by mass of aggregate [%]

D = dry density [kg/m^3]

Considering that latent cement is present within “pure” RCA material, it is important that the amount of cement that can be hydrated, and consequently carbonated, be quantified in an applicable method. For the purpose of this research study, the above equation was adapted to the following:

$$UCS = \left(\frac{pH}{MC_{test}}\right)^A * \left(\frac{DD_{test}}{1000}\right)^B \quad (5\text{-}2)$$

Where,

A, B = Coefficients that will be developed for this research

pH = pH-value of the material

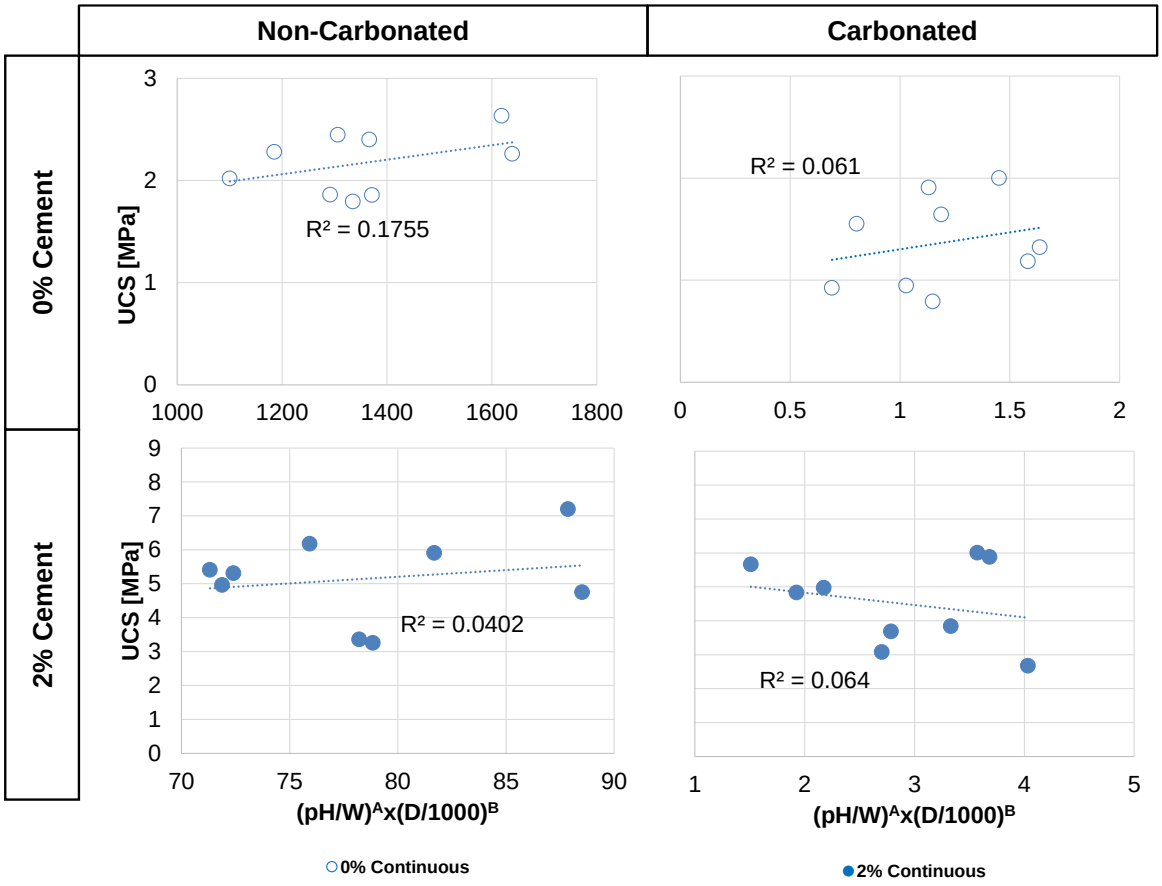
MC_{test} = Moisture content at time of testing [%]

DD_{test} = Dry density at time of testing [kg/m^3]

The cement content was substituted with pH, with the motive that only two cement contents were analysed in this research study, one of them being 0%. Therefore, with the pH-value being an indicator of cement content, the substitution therewith was justified and certainly more explicit.

The first step included modelling the data without distinguishing between the individual curing times (1, 7, and 28 days). This resulted in Figure 5-1 and Figure 5-2 for continuous and gap grade RCA, respectively. The A and B coefficients were chosen to optimise the regression coefficient, R^2, thereby presenting the ‘best fit’ linear relationship of the data being evaluated.

Figure 5-1 represents the results modelled with Equation 5-2 for non-carbonated and carbonated continuous grade RCA material. In all cases, this model results in poor correlations, however some trends were observed and necessitated further investigation.



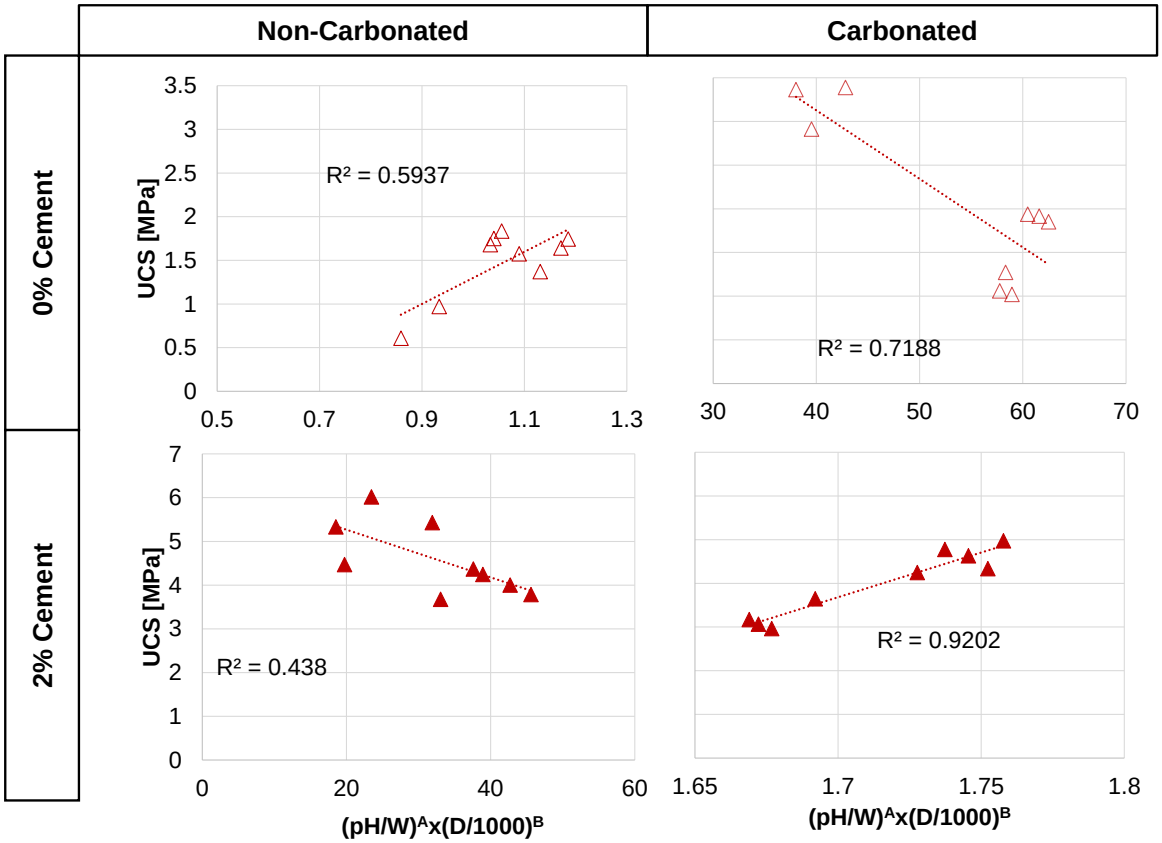
$$UCS\ [MPa] = \left(\frac{pH}{W}\right)^{A} x \left(\frac{D}{1000}\right)^{B}$$

W = Moisture Content [%] at Testing
C = pH at Time of UCS Test
D = Dry Density [kg/m³] at Testing
A and B are Coefficients in Table

Cement Added	Non-Carbonated		Carbonated	
	0%	2%	0%	2%
A	0.1	0.1	4.5	4.5
B	10	10	0.1	0.1

Figure 5-1: Influence of the Ratio of pH-value to the Moisture Content and the Dry Density on the UCS of Continuous Grade RCA for All Curing Times

Similarly, Figure 5-2 represents the results of the data of the gap grade RCA material modelled with Equation 5-2. Overall, the modelled data represents a better correlation compared to the continuous grade RCA (Figure 5-1).



$$UCS\,[MPa] = \left(\frac{pH}{W}\right)^{A} x \left(\frac{D}{1000}\right)^{B}$$

W = Moisture Content [%] at Testing
C = pH at Time of UCS Test
D = Dry Density [kg/m^3] at Testing
A and B are Coefficients in Table

Cement Added	Non-Carbonated		Carbonated	
	0%	2%	0%	2%
A	1	5	0.1	0.1
B	0.1	4.25	6	0.8

Figure 5-2: Influence of the Ratio of pH-value to the Moisture Content and the Dry Density on the UCS of Gap Grade RCA for All Curing Times

Cognisance of the fact that a high correlation coefficient does not necessarily imply that data is well modelled is confirmed by the spread of the data in Figure 5-2. In conclusion, most of the data is clustered and does not show predictive trends that can be utilised with confidence.

In evaluating the A-coefficient, which represents the degree of influence that the ratio pH/W has on the UCS of the material, and similarly, the B-coefficient, which indicates the degree of which the dry density of the material has on the UCS of the material, the following is concluded:

- The results of the coefficients used to model the UCS of the continuous grade non-carbonated RCA material is influenced more by the dry density of the material than the ratio of pH/W

- The results of the coefficients used to model the UCS of the continuous grade carbonated RCA material is influenced more by the pH/W ratio than the dry density of the material (this is the inverse of the non-carbonated continuous grade RCA material).

- The results of the coefficients used to model the UCS of the gap grade non-carbonated RCA material indicated that the ratio pH/W and dry density influenced the model differently for the material with 0% added cement than that with 2% added cement. With the latter indicating that both the ratio pH/W and dry density have near-equal influence on the UCS of the material. The data of the material with 0% added cement implies that there is a linear relationship between UCS and the ratio pH/W and that the dry density has very little influence on the UCS results.

- The results of the coefficients used to model the UCS of the gap grade carbonated RCA material showed a similar outcome, however, inverse to that of the non-carbonated gap grade RCA material.

Overall, these findings only tell part of the story and further delineation was needed as the general trends that are seen in Figure 5-1 and Figure 5-2 indicate that different variables could be concurrently influential at different curing times. To gain better understanding, the results were further categorised in terms of the curing time and modelled accordingly. These results showed a significantly improved correlation and are presented in Figure 5-3 and Figure 5-4 for continuous grade RCA material with 0% and 2% added cement, respectively.

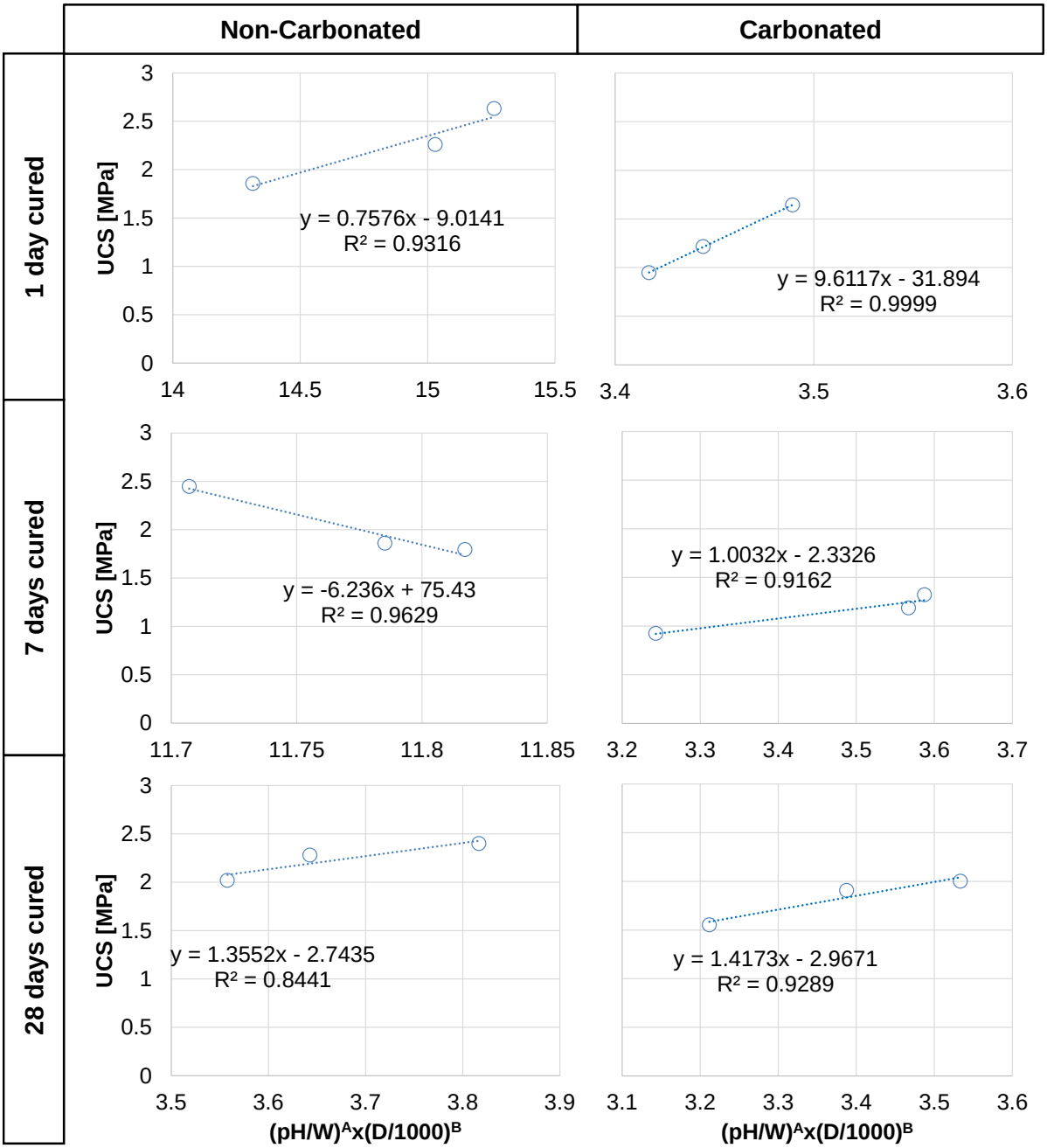


Figure 5-3: Influence of the Ratio of pH-value to the Moisture Content and the Dry Density on the UCS of Continuous Grade RCA for Individual Curing Times (0% Cement Addition)

Figure 5-3 represents a good correlation for the data modelled for the continuous grade RCA material with 0% added cement. The same can be said for Figure 5-4 to follow.

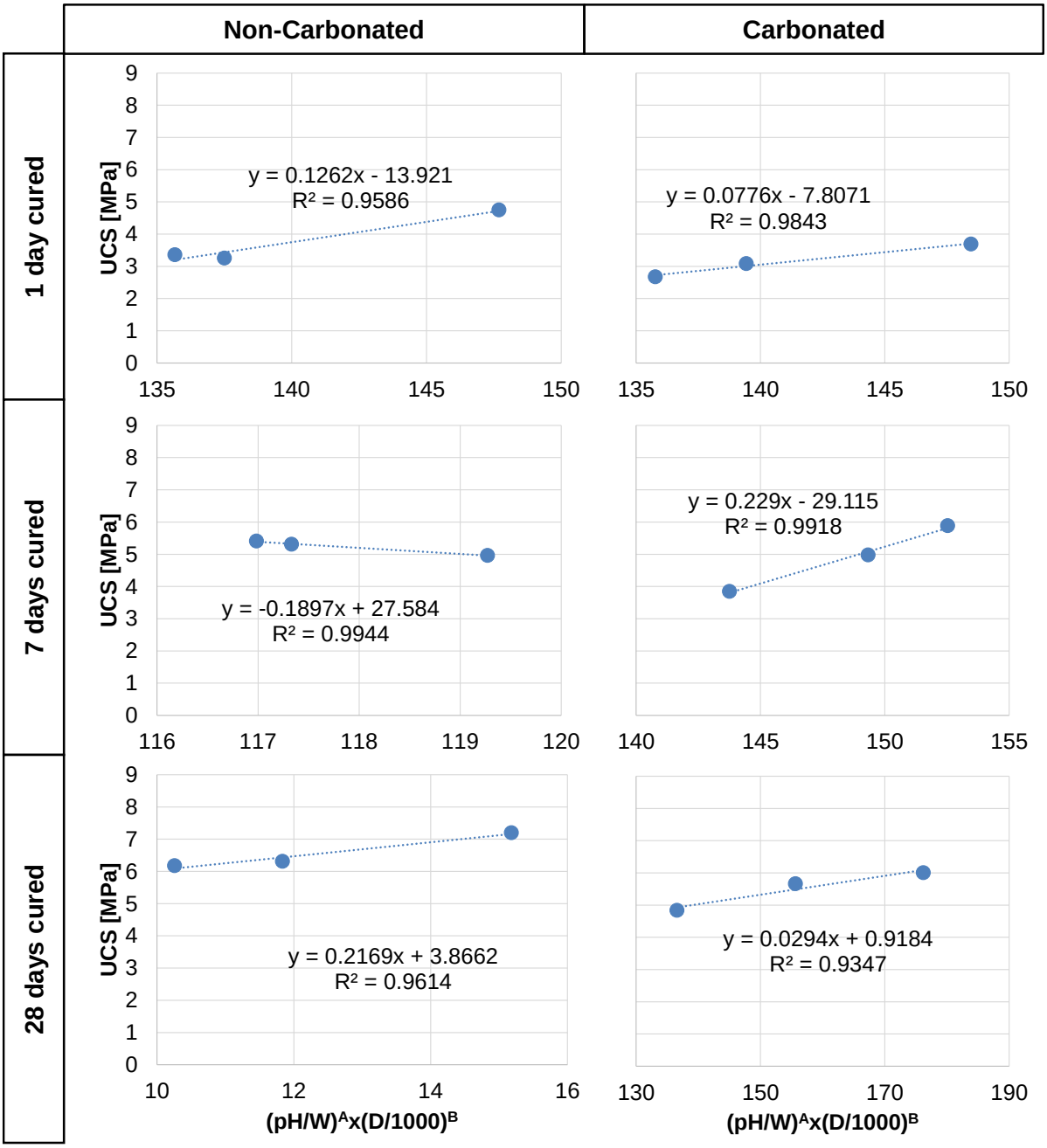


Figure 5-4: Influence of the Ratio of pH-value to the Moisture Content and the Dry Density on the UCS of Continuous Grade RCA for Individual Curing Times (2% Cement Addition)

Similarly, Figure 5-5 and Figure 5-6 represent the modelled data for gap grade RCA material with 0% and 2% added cement, respectively. Here too, good correlation (without clustering) is shown when the modelled data is divided into respective curing days and modelled with the appropriate coefficient were evident in both the non-carbonated and carbonated specimens.

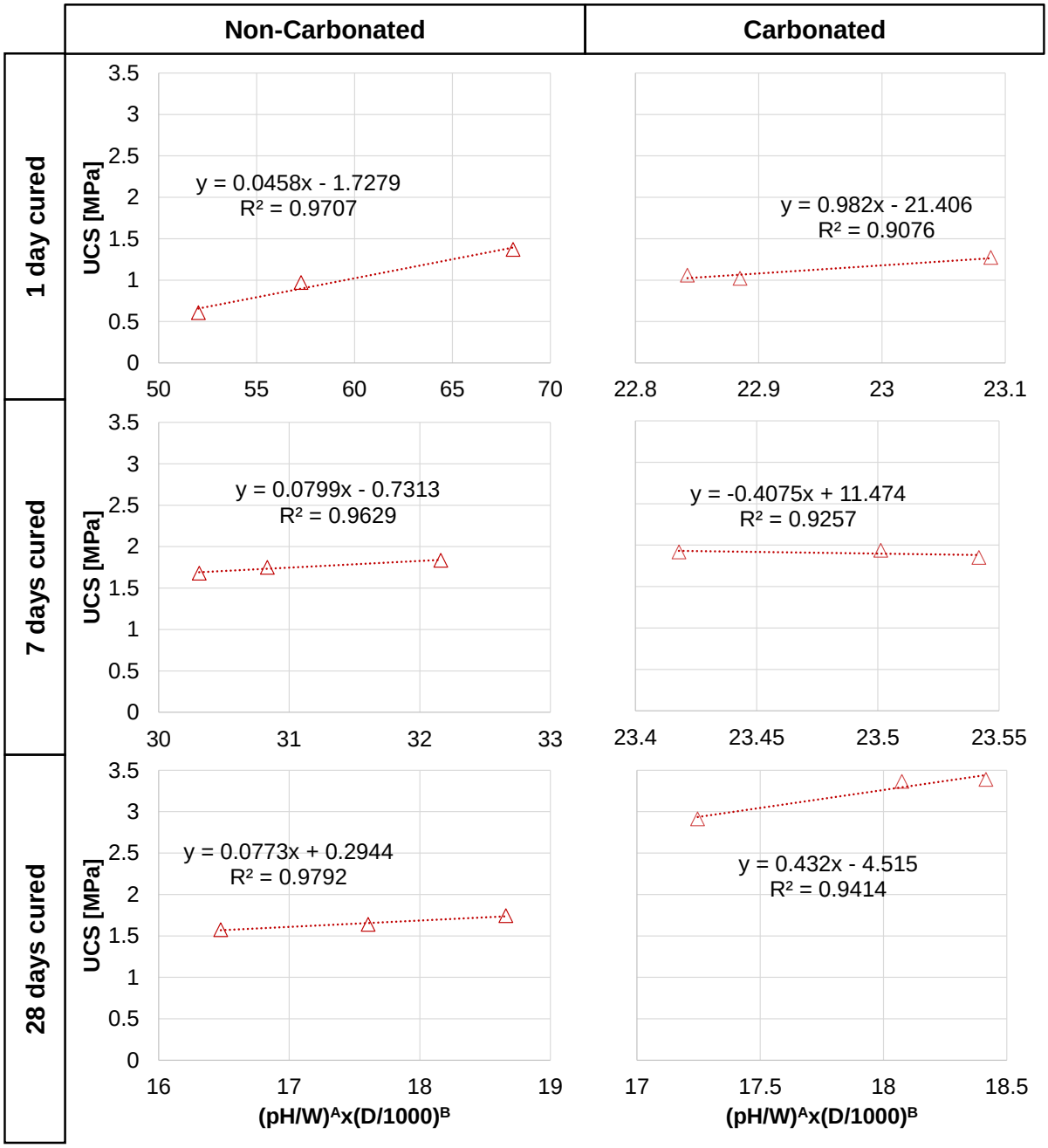


Figure 5-5: Influence of the Ratio of pH-value to the Moisture Content and the Dry Density on the UCS of Gap Grade RCA for Individual Curing Times (0% Cement Addition)

It is clear that, within its own clusters, these results are well correlated with a changing A- and B-coefficient and substantiate the claim that the influence of the different variables at varying curing times is evident.

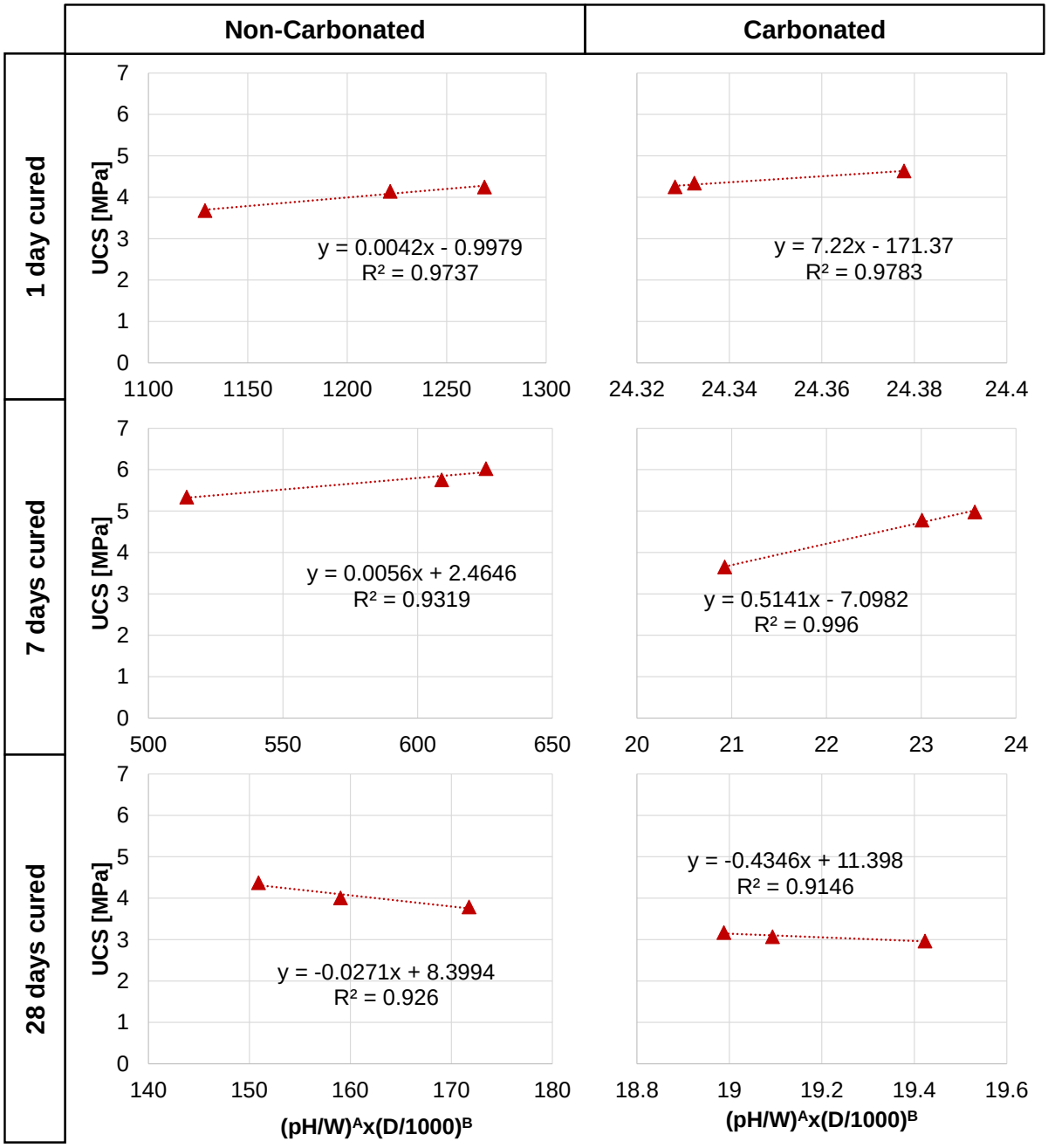


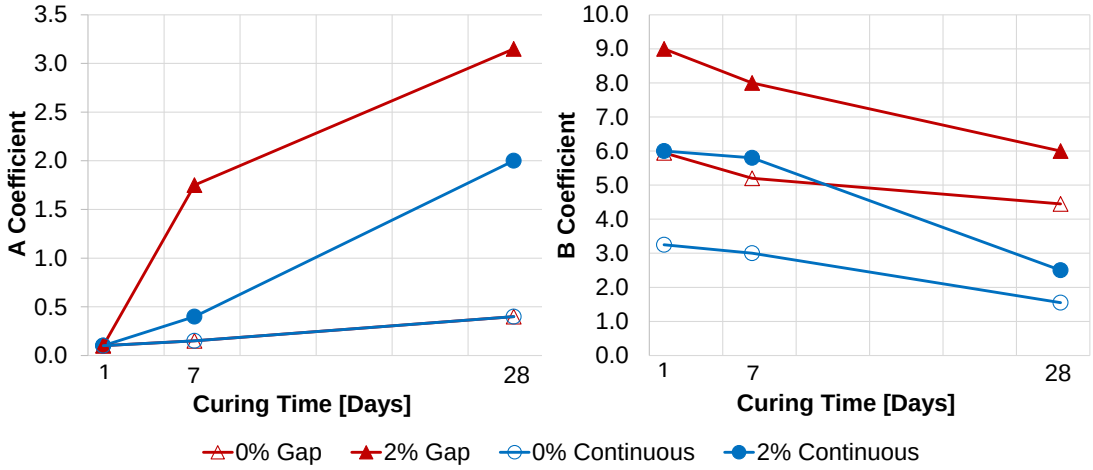
Figure 5-6: Influence of the Ratio of pH-value to the Moisture Content and the Dry Density on the UCS of Gap Grade RCA for Individual Curing Times (2% Cement Addition)

Figure 5-7 represents the A and B coefficients for non-carbonated RCA material at curing times of 1, 7, and 28 days. Initial observation of Figure 5-7 show that at a curing time of 1 day, the ratio pH/W has equal influence on both continuous and gap grade RCA material, irrespective of cement content. The ratio pH/W gains significance in the UCS model as curing time is increased, specifically for RCA material with 2% added cement. The A-coefficient for gap grade RCA, with 2% added cement, increases linearly through 1, 7, and 28 days. Although, for continuous grade RCA, with 2% added cement, the increase in influence of the

A-coefficient is steeper between the 7 and 28 days curing period compared to that of the gap grade. As for RCA material with 0% added cement, both continuous grade and gap grade RCA material depict the same linear increase of the A-coefficient for an increase in curing time.

Furthermore, the B-coefficient, which indicates the influence of dry density on the UCS result, (for non-carbonated RCA material in Figure 5-7) depicts an obvious shift in influence for the various material grading's as well as added cement content. For both material grading's, the RCA material with 2% added cement indicates that the dry density of the material has the greatest influence on UCS at a curing time of 1 day. The influence of density decreases linearly with increasing curing time with the gap grade RCA material (with 2% added cement) showing a gradual linear decrease through all curing times. The continuous grade RCA material (with 2% added cement) shows a lower linear decrease between curing times of 1 and 7 days which decreases more rapidly between curing times of 7 and 28 days. These observations of the B-coefficient respond well with those of the A-coefficient with a similar inverse trend, observed for the latter. The RCA material with 0% cement added, simulate the trends discussed regarding their equivalent material grading's with 2% added cement.

A and B Coefficients: Non-Carbonated



Material Grading	Coefficient	0% Cement Added			2% Cement Added		
		1	7	28	1	7	28
GAP	A	0.1	0.25	0.4	0.1	1.75	3.15
	B	5.95	5.2	4.45	9	8	6
CONTINUOUS	A	0.1	0.25	0.4	0.1	0.4	2
	B	3.25	3	1.55	6	5.8	2.5

Figure 5-7: Values of A and B Coefficient's for Non-Carbonated RCA Material

Holistically and in summary, this data is interpreted as follows:

Considering the A-coefficient:

- pH/W ratio has the same influence on the UCS of RCA material at a curing time of 1 day for continuous and gap grade RCA and is unrelated to the added cement content.
- pH/W ratio has the same influence on UCS, irrespective of material grading, for RCA material with 0% added cement over the curing period. This influence of this ratio increases, marginally, with increasing curing times.
- pH/W has a greater influence on UCS for gap grading material at 7 and 28 days curing time in relation to continuous grade RCA material.

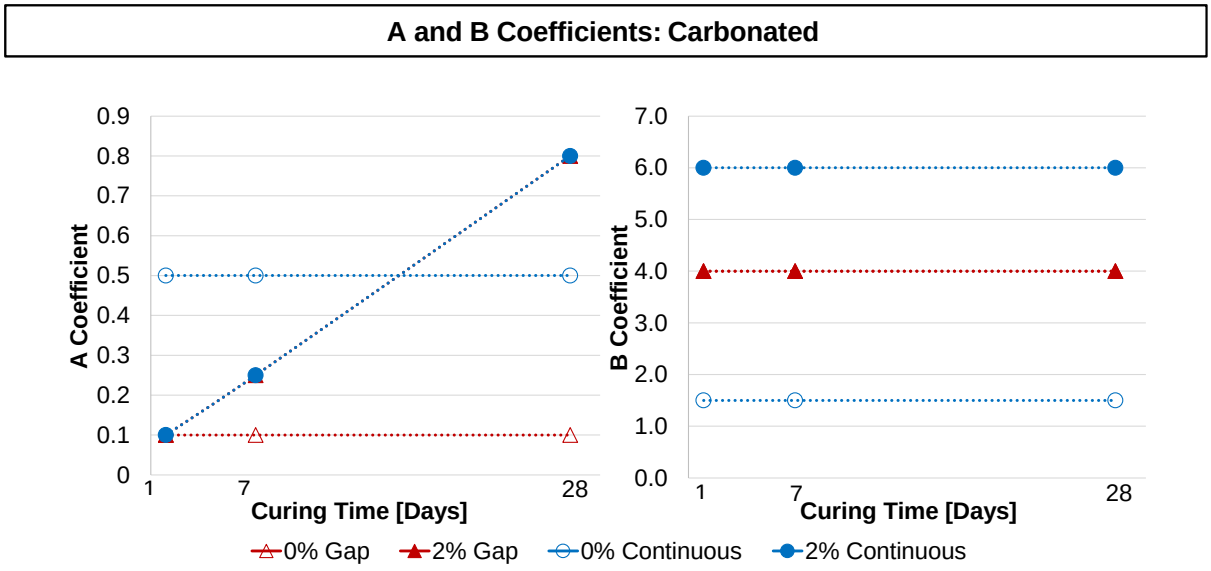
Considering the B-coefficient:

- The dry density of RCA material depicts a superior influence on material with 2% added cement than material to which no cement was added.
- The dry density of gap grade RCA material has a greater influence on the UCS material compared to continuous grade RCA material.

Figure 5-8 represents the A and B coefficient used in the model expressed in Equation 5-2 for carbonated RCA material. As described previously, the A-coefficient indicates the influence of the ratio pH/W on the UCS of continuous and gap grade RCA material. Similarly, the B-coefficient indicates the influence of dry density on the UCS of continuous and gap grade RCA material.

Considering Figure 5-8, the A-coefficient corresponds well for the two material grading's used. For the RCA material, with 0% added cement, both material grading's show no change in influence of the ratio pH/W at over the curing periods. Continuous grade RCA material is somewhat more sensitive to this ratio than gap grade RCA material. In the case of RCA material with 2% added cement, both grading's of carbonated RCA material have an equal positive linear relationship between the A-coefficient and increased curing time.

The B-coefficient remains constant, at 4.0 for carbonated gap grade RCA material at increasing curing times and falls somewhere in between the B-coefficient for continuous grade RCA material with 0% added cement and 2% added cement, respectively. The B-coefficient of continuous grade RCA material, with 2% added cement, is considerably higher than that of continuous grade RCA material with no added cement.



Material Grading	Coefficient	0% Cement Added			2% Cement Added		
		1	7	28	1	7	28
GAP	A	0.1			0.1	0.25	0.8
	B	4.0			4.0		
CONTINOUS	A	0.5			0.1	0.25	0.8
	B	1.5			6.0		

Figure 5-8: Values of A and B Coefficient's for Carbonated RCA Material

In summary this table indicates how, with reference to the gap and continuous grading, there is some influence i.to. the pH/W ratio at 0%, but this does not change with time. Similarly, the density coefficient B at 0% also does not change with time. It does suggest that the 0% is not to susceptible in carbonation i.e. its reliance on the cement strength as part of its performance properties to start with and one of the questions asked in this research.

In contrast the in pH/W ratio becomes more significant with time when 2% cement is considered, i.e. truly as a stabilised material.

5.2 Modelling the relationship between UCS and ITS

Following the development of the relationship between the intrinsic variables and the strength parameter, UCS, it seems imperative to gain understanding of how these relationships relate to the pavement life of RCA materials. The pavement life is typically related to the fatigue parameters of a material, such as the ITS. Although the ITS results collected in this research study have not been related to intrinsic parameters, as with the case of the UCS results, they will be used as an indicator of the performance of RCA material in terms of the pavement life.

This is validated as the relationship between UCS and direct and/or indirect tensile strength has been researched extensively and some examples are given below in Table 5-2.

Table 5-2: Relationship between UCS and Direct/Indirect Tensile strength (Adopted from Xuan (2012))

Material	Prediction models of Tensile strength	Reference	Remarks
CTG_rM	$DTS = 0.10 \cdot UCS$	(Balbo, 1997)	-
	$f_f = a \cdot UCS$	(Kolias & Williams, 1984)	The coefficient, a, is influenced by mixture parameters.
	$f_f = 0.25 \cdot UCS^{0.75}$		
	$ITS = a \cdot UCS + b$ $ITS = a' \cdot UCS$	(Kolias & Williams, 1980)	

Furthermore, the TRH13 (1986) identifies an approximate relationship between the ITS and UCS of material as follows:

$$ITS = 0.13UCS \tag{5-3}$$

This can be written as a ratio:

$$\frac{UCS}{ITS} = 7.69 \tag{5-4}$$

It is however stressed that this relationship has a weak correlation and should therefore not be used to estimate values.

For this reason, alongside the UCS results (for non-carbonated and carbonated RCA), the ITS results are used to determine if correlations are present. Ultimately, by obtaining a good correlation between UCS and ITS, the intrinsic variables (previously related to the UCS results) can indirectly be associated with the ITS results. Furthermore, these relationships will exist for both non-carbonated and carbonated RCA material and if a pavement life is calculated for both of these material conditions, the influence hereof can be estimated.

The first step is performed by a graphical representation of UCS versus ITS of non-carbonated RCA material of two grading types and two cement contents which is compared to that of carbonated RCA material.

Figure 5-9 represents the data of UCS and ITS results for non-carbonated and carbonated RCA material of two grading types with 0% added cement and 2% added cement.

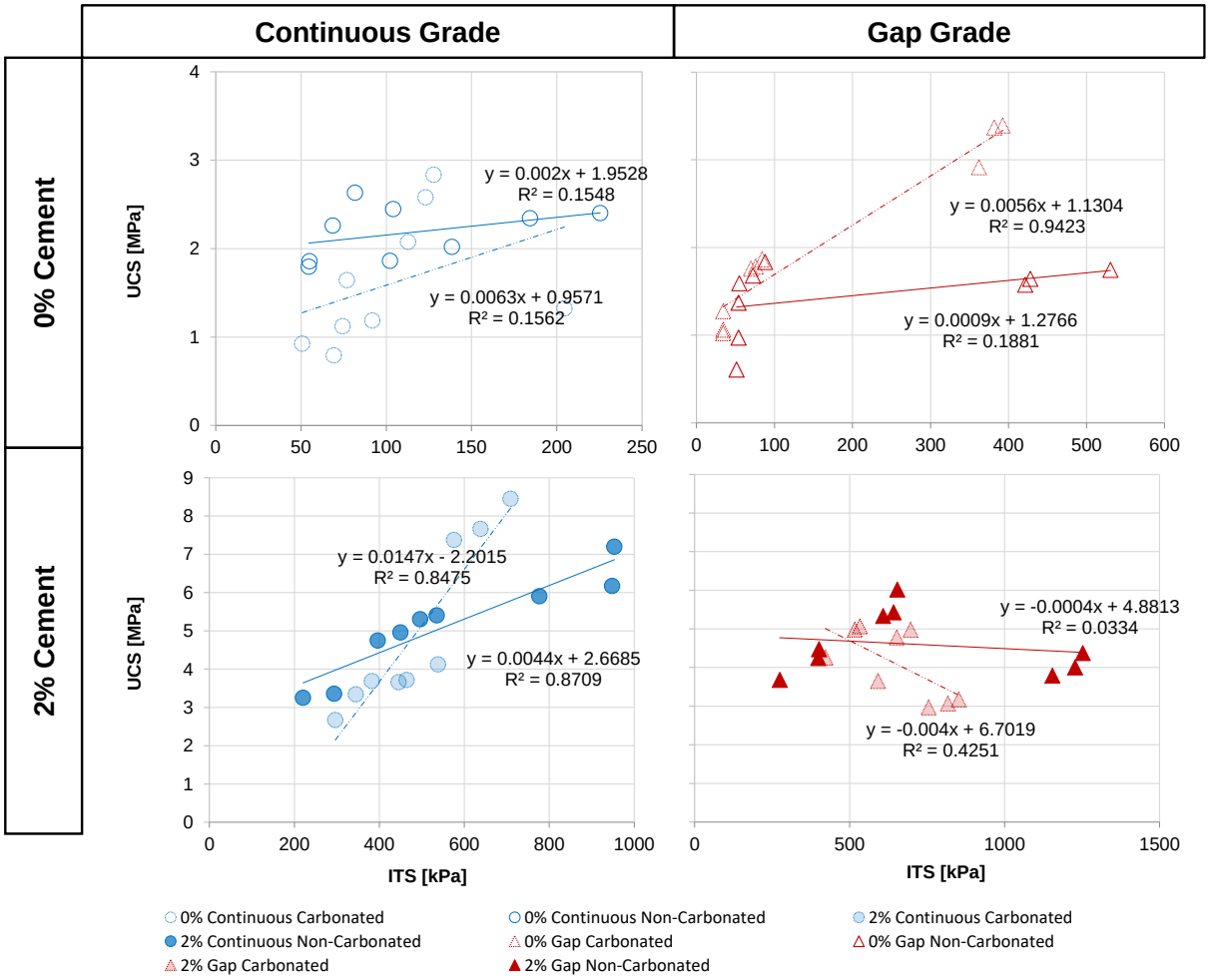


Figure 5-9: Relationship between UCS and ITS of Continuous and Gap Grade RCA Material

The data presented in Figure 5-9 shows a weak correlation for the gap grade RCA with the exception of the carbonated specimens with 0% added cement. These weak results can be attributed to the data representing specimens cured for 28 days. These specific specimens showed to have significantly lower densities and will be omitted for further discussion.

Furthermore, the continuous grade RCA also hold weak correlation between the UCS and ITS where 0% cement was added. With the addition of 2% cement, this relationships improves significantly. Taking a step back, to gain better understanding of the influence which carbonation has on the relationship between UCS and ITS of RCA, data for both cement contents is plotted on the same graph in Figure 5-10 below. These results represent the UCS and ITS of continuous grade and gap grade RCA material.

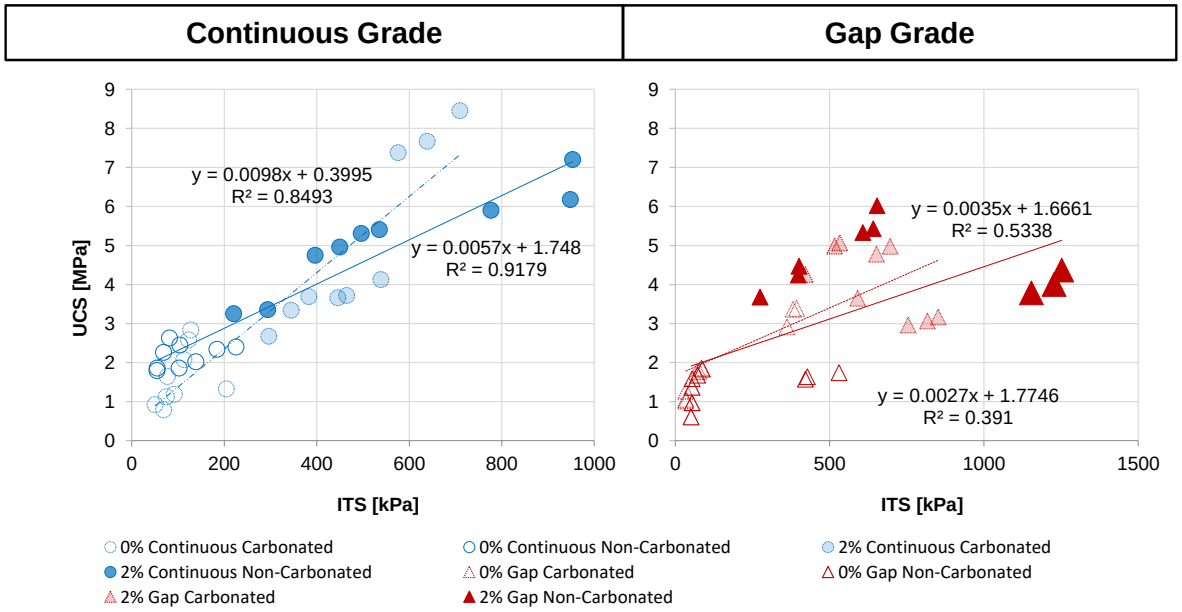


Figure 5-10: Relationship between UCS and ITS of Non-Carbonated and Carbonated RCA Material

Considering simply the continuous grade RCA material, the regression line shows a positive correlation of 0.849 and 0.918 for carbonated and non-carbonated material, respectively. An envelope can be used to better describe the range of expected values, as the curing time has a direct influence on the development of both the UCS and ITS results.

The gradient of the carbonated continuous grade RCA material (represented by the dotted line) is slightly steeper than the non-carbonated continuous grade RCA material. This can be attributed to the substantial improvement in UCS results at 28 days curing time as a result of carbonation. Contrary, the ITS results at 28 days curing decrease as a result of carbonation when considering the continuous grade RCA material, with 2% added cement.

The results of the gap grade RCA material depict a somewhat better UCS/ITS relationship of the carbonated material than that of the non-carbonated material, however both remain weak.

To allow for direct comparison of the influence of carbonation on the UCS/ITS relationship, in terms of the grading thereof, it is decided to omit the results of the 28 days curing time. The reason being that these results are influenced negatively by the weak densities achieved of the gap grade specimens and in terms of the continuous grade specimens, the UCS/ITS relationship appears skewed at 28 days. The corresponding results are shown in Figure 5-11.

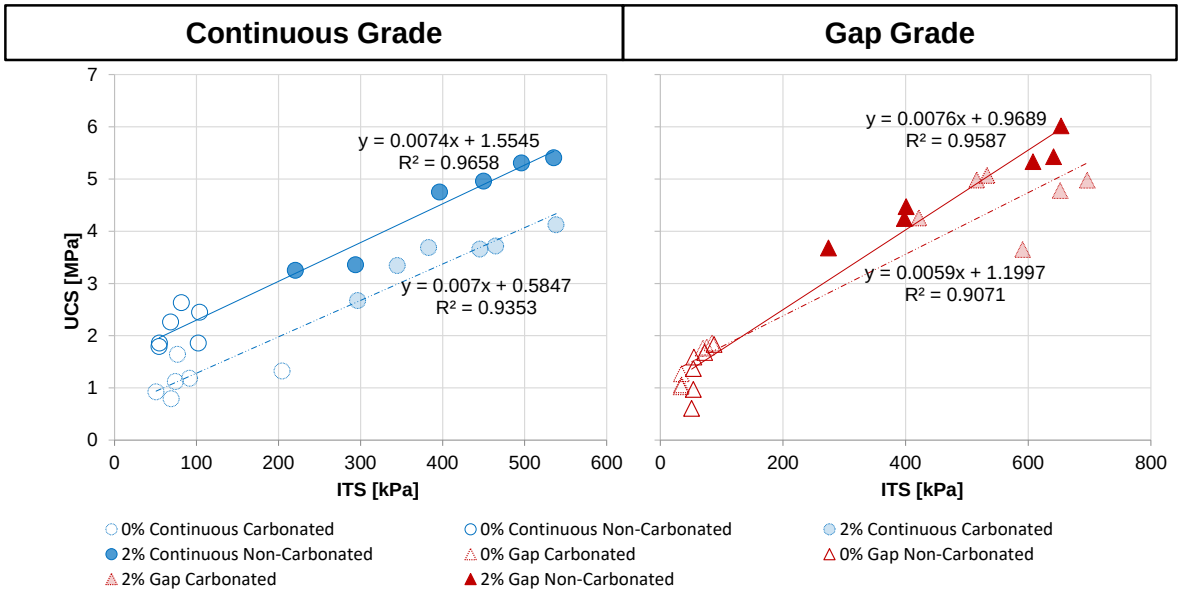


Figure 5-11: Relationship between UCS and ITS of Continuous Grade RCA Material and Gap Grade RCA Material (results at 28 days curing time omitted)

Considering the results of the continuous grade RCA material, represented in Figure 5-11, the relationship between UCS and ITS is expressed as follows for the curing period 1-7 days:

- Non-Carbonated: UCS = 0.0074 x ITS + 1.55
- Carbonated: UCS = 0.007 x ITS + 0.56

And for 28 days, respectively:

- Non-Carbonated: UCS = 0.007 x ITS - 0.04
- Carbonated: UCS = 0.008 x ITS + 2.62

Considering the results of the gap grade RCA material represented in Figure 5-11 the relationship between UCS and ITS is expressed as follows for the curing period 1-7 days:

- Non-Carbonated: UCS = 0.0076 x ITS + 0.97
- Carbonated: UCS = 0.0059 x ITS + 1.20

And for 28 days, respectively:

- Non-Carbonated: UCS = 0.005 x ITS - 2,33
- Carbonated: UCS = 0.0021 x ITS + 1,40

The results of the gap grade RCA, as shown in Figure 5-11, depict a different effect of carbonation on the relationship between UCS and ITS compared to that of the continuous grade results. It can be seen that carbonation of the gap grade RCA material, at a curing time of 1 day, shows to improve the relationship between UCS and ITS and the opposite is

observed at a curing time of 7 days. However, with cognisance of the fact that the y-intercept of the non-carbonated and carbonated results are extremely close together (i.e. 0.9689 vs 1.1997, respectively) one could very well then conclude that there is not an apparent difference at 1 day but that the effect of carbonation decreases over time.

In conclusion, these results are interpreted as follows:

- The relationship between UCS and ITS of non-carbonated continuous grade RCA material is better than that of the same material which has been carbonated. Hence, it is shown that the UCS results of the non-carbonated continuous grade RCA are approximately 1MPa higher.
- The relationship between UCS and ITS of the carbonated continuous grade RCA material at a curing time of 28 days is shown to be better than the material which was not carbonated.
- The relationship between UCS and ITS of carbonated gap grade RCA material is better at a curing time of 1 day and is shown to be worse at a curing time of 7 days, in comparison to the results of the non-carbonated RCA material.

A summary of the influence which carbonation has on the ratio between UCS and ITS for continuous grade and gap grade RCA material at various curing times, no cement and 2% added cement content is summarised in Table 5-3.

Table 5-3: Summary of Ratio of UCS/ITS of Continuous Grade and Gap Grade RCA Material

RCA Material Grading	Curing Time	Added Cement	UCS/ITS of Non-Carbonated RCA Material	UCS/ITS of Carbonated RCA Material	Did Carbonation Improve the Ratio UCS/ITS
Continuous Grade	1 Day Cured	0%	0.033	0.016	No
	7 Days Cured		0.025	0.013	No
	28 Days Cured		0.013	0.021	Yes
	1 Day Cured	2%	0.013	0.009	No
	7 Days Cured		0.011	0.008	No
	28 Days Cured		0.007	0.012	Yes
Gap Grade	1 Day Cured	0%	0.018	0.032	Yes
	7 Days Cured		0.024	0.024	No
	28 Days Cured		0.004	0.008	Yes
	1 Day Cured	2%	0.012	0.010	No
	7 Days Cured		0.009	0.007	No
	28 Days Cured		0.003	0.004	Yes

The results of Table 5-3 have been interpreted as follows:

Continuous Grade RCA Material:

- The UCS/ITS ratio is improved when continuous grade RCA material is carbonated at 28 days curing time, irrespective of added cement.
- The UCS/ITS relationship exceeds that which is represented in equation (5-4), in most cases, with the exception of non-carbonated continuous grade RCA material with 2% added cement at 28 days curing time (7.22<7.69)

Gap Grade RCA Material:

- The UCS/ITS ratio was improved by carbonating the material, with 0% added cement, at a curing time of 1 day.
- The UCS/ITS ratio was improved by carbonating the material at a curing time of 28 days, however, these results are only added for interest sake as the densities of this material batch was significantly lower than the target density of the gap grade RCA material.

5.3 Conclusions

From the analysis it is important to note that a simple linear relationship without considering dependency of variables are entirely insufficient as shown in the analysis Chapter 4. However, considering a model that allows for non-linearity of the variables, and also interdependency, correlations do manifest. It is clear from the results that a correlation between the UCS and the considered intrinsic variables do exist. This holds true for both non-carbonated and carbonated specimens. However, it is important to understand that the significance of one variable might change through the development of the cementitious bonds, especially in the case of cemented stabilised materials (i.e. specimens which had 2% addition of cement).

Regarding this, correlations with variables for UCS were developed for both gap and continuous grade materials. In turn a relationship between UCS and ITS were formulated. This allows for distinguishing how a particular variable could influence the carbonation of the material and allows for the scope of understanding the influence which carbonation could have on the pavement life which is discussed next.

CHAPTER 6: SIGNIFICANCE TO INDUSTRY

This chapter includes addresses how the information presented thus far could benefit industry. Two scenarios are investigated and in an attempt to give insight into understanding and articulating the results on a practical level. The two questions under consideration are as follows:

- Question 1: Considering the (intrinsic) variables, how does carbonation influence pavement life?
- Question 2: Is carbonation an issue when considering RCA with no new addition of cement (0% RCA)?

The discussions to follow aim to investigate these questions as far as possible, with reference to the current information as well as the risk associated with these.

6.1 Question 1: Considering the (intrinsic) variables, how does carbonation influence pavement life?

To answer this question, some typical pavement scenarios are analysed. This process involves the following steps:

- Choose the pavement layer works to be investigated. (Section 6.1.1)
- Choose a UCS value typical for a stabilised material. (Section 6.1.1)
- Obtain the horizontal strain at the bottom of the layer, for a particular loading scenario. (Section 6.1.2)
- Determine the ITS using the relationships developed in Chapter 6 and calculate this for non-carbonated and carbonated material. (Section 6.1.3)
- Use a fatigue relationship to determine the pavement life. (Section 6.1.4)
- Compare the different pavements and variables to analyse and understand the sensitivity to variables in practical terms. (Section 6.1.5).

6.1.1 Typical pavements to be analysed:

A typical South African pavement is considered to evaluate the potential impact of different variables brought forward in this research study.

The pavement layers consist of a seal surfacing, G2 base, typical C3 subbase, G5 selected subgrade and a G7 in-situ subgrade. The thickness of the pavement layers are provided in Figure 6-1 and is representative of a typical pavement layer thickness as in the TRH4 (2013). The assumed stiffness values, presented in Figure 6-1, are typical values as suggested by

Theyse (2000), however, no stiffness is allocated to the seal surfacing as it has no structural contribution. The G2 base layer is divided into three equal layers and an iterative process used to determine the Resilient Modulus (M_r) of these layers. The typical model, $M_r = k_1\varphi^{k2}$, is used to determine the final M_r, before values are extracted for further calculations.

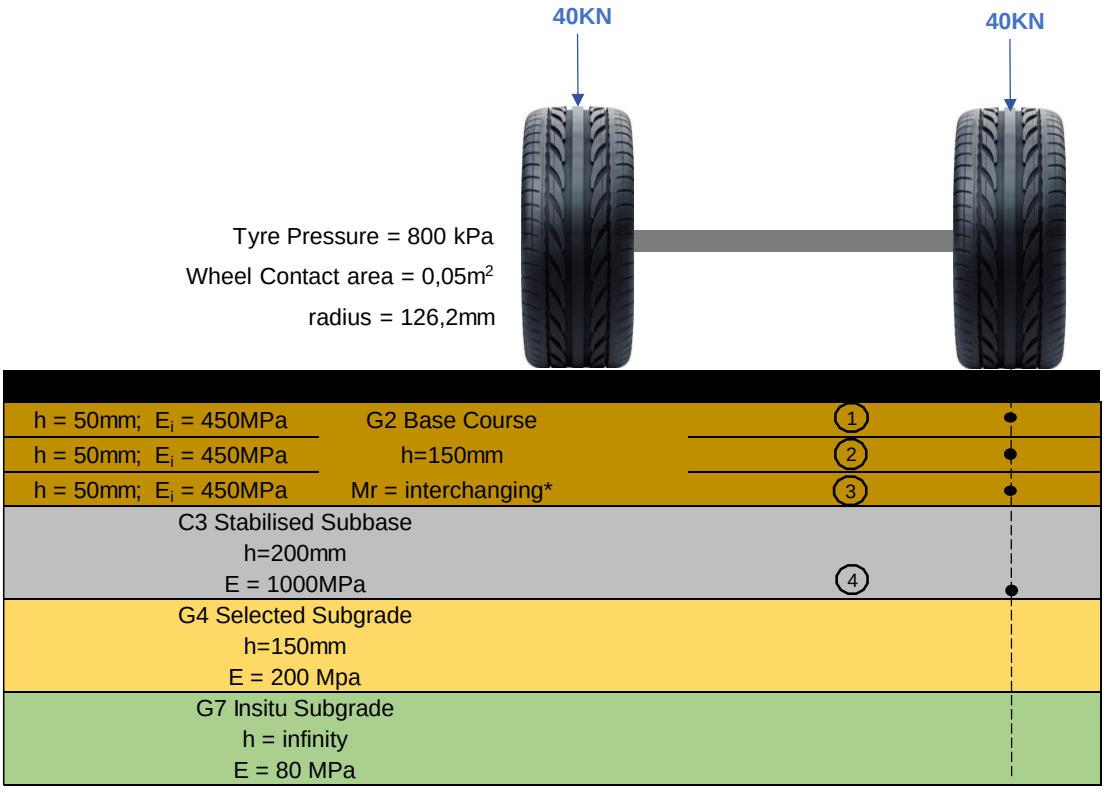


Figure 6-1: Pavement layer works, material properties and position of measurements

The standard axle configuration can be either a single or dual wheel load (SAPEM, 2014), for the purpose of this research study, a dual wheel load is selected. A typical standard axle load of 80kN is applied (i.e. 40kN per wheel) and the position of measuring the stresses and strains within the layer are shown in Figure 6-1. Generally, the horizontal and vertical stresses are critical at the centre position of a granular layer as this layer will fail in shear. For fatigue of the C3 cemented subbase, the horizontal strain is taken at the bottom of the layer.

Morton *et al.* (2004) suggests typical ranges of tyre pressures which has increased significantly over the years from the original 520kPa in previous years. For this reason, a tyre pressure of 800kPa was chosen as representative. Furthermore, a typical Road Category B, which coincides with a 90% Reliability, is considered for this analysis.

6.1.2 Determine the Horizontal Strain

MePads, a software programme developed by the Council for Scientific and Industrial Research (CSIR) was employed to perform a linear elastic analysis on the pavement. An iterative process was followed in order to determine the stresses and strains at the identified positions.

The process involves assuming an initial M_r value for each of the 50mm base sub-layers. Applying the chosen M_r model (in this case the $k_1\varphi^{k2}$ model), the reported horizontal and vertical stresses are substituted and the results used to determined how different (% difference) this is from the seed value. This iteration process is continued until convergence is attained between the chosen and calculated M_r value. A value difference in M_r lower than 10% is acceptable for a Road Category B.

The k_1 and k_2 values, used to define the coefficients of the M_r model, are taken from research done by van den Berg (2014). When this is reached two considerations is very important, that is the prescribed Modular Ratio as well as the maximum allowable Mr that may be used as boundary condition cap these values at a certain point due to the support given by underlying layers. The results of this analysis are provided in Table 6-1.

Table 6-1: Summary of MePads stresses and strains outputs

Iteration	Position	MePads Values			ε_h	φ	k1	k2	Mr (MPa)	Mr Iteration (% Difference)	Cap
		σ1(kPa)	σ1(kPa)	σ1(kPa)							
3	1	792,8	536,6	536,6	-	1866	25,6	0,485	987,72	-1	550
	2	705,1	214,8	214,8	-	1135			775,99	-1	550
	3	545	174,1	174,1	-	893			690,96	0	550
	4	-	-	-	142	-	-	-	-	-	-

6.1.3 Determine the Indirect Tensile Strength using developed Relationships

Following the calculation of the stresses and horizontal strain, the resistance of the materials can be determined. This is determined by using the formulated UCS and ITS relationships together with the average drop or increase of UCS due to carbonation. The UCS and ITS relationship for curing period of 7 days is used in particular as a result of the challenges encountered with the specimens cured for 28 days. These challenges are discussed in previous chapters and include the low densities achieved for the gap grade specimens. Nonetheless, the outputs of these results can show insightful findings.

The choice of using ITS, rather that UCS, as the “strength parameter” emanates from the failure mode in cemented subbases being tension. There are many relationships available in literature that converts UCS values to direct tensile strength (DTS), but ITS results are

available after this has been developed and differ for non-carbonated and carbonated material, probably due to different variables having an influence on the UCS and ITS results.

Considering the results of the continuous and gap grade RCA material, the developed relationship between UCS and ITS is expressed as follows (as determined in the Chapter 5):

Continuous:

- Non-Carbonated:

$$UCS = 0.007\ x\ ITS + 1.56 \quad (6\text{-}1)$$

- Carbonated:

$$UCS = 0.007\ x\ ITS + 0.59 \quad (6\text{-}2)$$

Gap:

- Non-Carbonated:

$$UCS = 0.0076\ x\ ITS + 0.97 \quad (6\text{-}3)$$

- Carbonated:

$$UCS = 0.0059\ x\ ITS + 1.20 \quad (6\text{-}4)$$

Continuous (7 day):

- Non-Carbonated:

$$ITS = \left(\frac{UCS - 1.56}{0.007}\right) \quad (6\text{-}5)$$

- Carbonated:

$$ITS = \left(\frac{UCS - 0.59}{0.007}\right) \quad (6\text{-}6)$$

Gap (7day):

- Non-Carbonated:

$$ITS = \left(\frac{UCS - 0.97}{0.0076}\right) \quad (6\text{-}7)$$

- Carbonated:

$$ITS = \left(\frac{UCS - 1.20}{0.0059}\right) \quad (6\text{-}8)$$

It should also be noted that the ITS is an indirect test and the TRH13 (1986) suggests that:

$$DTS = \frac{ITS}{1.5} \quad (6\text{-}9)$$

This relationship is considered when calculating the tensile strain resistance. The results of the steps involved in calculating this are presented in Table 6-2 (Steps 1-3). In addition, for sensitivity analysis, a range of UCS values (3-5.5MPa) are chosen as indicated taking cognisance of the fact that these higher UCS values are not typical for a C3 material and this should be considered further.

Table 6-2: Calculating the Pavement Life of the Cemented Subbase

Step 1: Indirect Tensile Strength (kPa)				
Grading Type				
UCS (MPa)	Continous		Gap	
	Non-Carbonated	Carbonated	Non-Carbonated	Carbonated
3	205,71	182,86	267,25	27,75
3,5	277,14	254,29	333,04	93,54
4	348,57	325,71	398,83	159,33
4,5	420,00	397,14	464,62	225,12
5	491,43	468,57	530,41	290,91
5,5	562,86	540,00	596,20	356,70
Step 2: Direct Tensile Strain (Microstrain)				
Grading Type				
UCS (MPa)	Continous		Gap	
	Non-Carbonated	Carbonated	Non-Carbonated	Carbonated
3	137,14	121,90	178,17	18,50
3,5	184,76	169,52	222,03	62,36
4	232,38	217,14	265,89	106,22
4,5	280,00	264,76	309,75	150,08
5	327,62	312,38	353,61	193,94
5,5	375,24	360,00	397,46	237,80
Step 3: Pavement Life (N x 10^^{6})				
Grading Type				
UCS (MPa)	Continous		Gap	
	Non-Carbonated	Carbonated	Non-Carbonated	Carbonated
3	0,82	0,62	1,34	0,00
3,5	1,42	1,23	1,85	0,06
4	1,96	1,79	2,30	0,44
4,5	2,43	2,29	2,69	0,98
5	2,83	2,71	3,02	1,53
5,5	3,17	3,06	3,31	2,02

To determine the pavement life, the typical fatigue relation for cemented materials (stipulated in the SAMDM) is used as the failure mechanism under consideration. The failure mechanism for the C3 layer is cracking at the bottom of the material layer due to horizontal tensile forces. Therefore, the tensile strain, positioned at the bottom of the layer, is used as the critical parameter for the subbase.

The Fatigue relationship, for a Road Category B, is presented as follows:

$$N = SF\ x\ 10^{6,84(1-\frac{\varepsilon}{7.63\varepsilon_b})} \quad (6\text{-}10)$$

Where,

N	=	Estimated Design life for a Road Category B
S_f	=	Shift factor due to layer thickness
ε	=	Tensile strain at bottom of the layer (calculated as142 microstrain)
ε_b	=	Strain at break, in this case as calculated for each scenario

In the current exercise, the impact of carbonation on the pavement life of the subbase layer is considered only. Although a pavement structure should be considered in its entirety when calculating the pavement life, the objective of calculating these results is only to compare the subbase life in its "bound phase" of the non-carbonated versus carbonated RCA material. Therefore, the pavement life (reported in Step 3 of Table 6-2) should not be taken as absolute values but rather as comparative against each other and unique to the results of this research study. These results are illustrated in Figure 6-2 below, where "NC" represents non-carbonated and "C" represents carbonated.

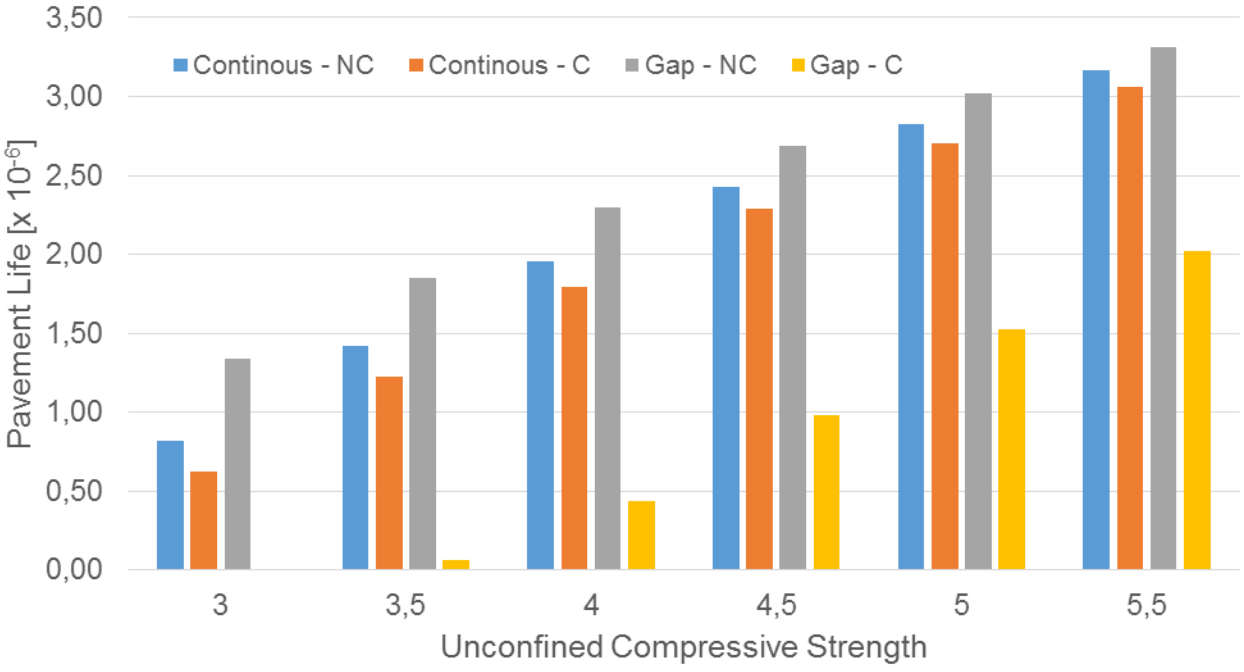


Figure 6-2: Pavement Life of Non-Carbonated and Carbonated RCA Material of Subbase Layer

These results indicate a significant drop in the pavement life for the gap grade RCA material as opposed to the continuous grade RCA material. In addition these results substantiate the findings of the lab results as well as in literature by Li (2012) which alludes to lightly cemented

materials being more susceptible to carbonation. Assuming of course that a lower UCS is indicative of lighter cementing. These results suggest that the choice of grading of RCA material is imperative and that good controls should be implemented to ensure maximum packing of the particles in order to provide resistance as far as possible against carbonation.

6.2 Question 2: Is carbonation an issue when considering RCA with no new addition of cement (0% RCA)?

The question still remains if industry should be concerned about carbonation of RCA, specifically without the addition of cement. As discussed in the Chapter 2, the latent self-cementing of RCA material is of considerable interest as this could potentially result in the RCA material performing as a lightly cemented material. This is also substantiated by van Niekerk, (2002).

A summary of the average percentage carbonation achieved for continuous and gap grade RCA material, with 0% addition of cement, is provided in Table 6-3.

Table 6-3: Average Carbonation Percentage of Continuous Grade and Gap Grade RCA Material (with 0% Cement Addition)

0% Cement Specimens Carbonated Together		Continuous Grade			Gap Grade		
Days Cured	Chamber Nr	UCS	ITS	CONTR	UCS	ITS	CONTR
1	1	95	93	97	97	90	65
7	1	95	80	70	95	85	-
28	1	82	77	90	97	72	62

These results indicate that, in most cases, near-full carbonation is observed for RCA material with 0% cement added (as reported in Chapter 4). In comparison, the RCA material with 2% addition of cement, showed less observed instances of such high degrees of carbonation.

Although it has not been noted explicitly elsewhere, 0% RCA was sprayed with phenolphthalein prior to testing to ensure that there was still latent cement present. In all cases this reflected a fuchsia-pink. Additionally, the results of the pH-value of the non-carbonated RCA material with 0% added cement were reasonably high and in the same order size as those with the addition of 2% cement. A summary of the average pH-value's for continuous grade RCA material (curing periods of 1 and 7 days) is provided in Table 6-3, as previously discussed in Chapter 4.

This particular grading together with the chosen curing times of 1 and 7 days was chosen due to the following reasons:

- A continuous grading would be the preferred choice due to matrix interlock; if crushing allow
- RCA with 0% added cement would typically be used as a granular material. Testing and laying of such material could happen in a short amount of time (an example is given later) as it is not necessary to be cured as a stabilised material would. The issue here is that the RCA material (with 0% added cement, however, with the presence of latent cement) will be susceptible to durability issue related to typical stabilised materials, from early stages.

With reference to Table 6-3, which summarise the average of the results shown in Figure 4-17, the results reveal a significant decrease in pH-value as well as UCS as a result of carbonation. This results are particularly low when compared to the same material with a 2% addition of cement (refer to Chapter 4).

Table 6-4: Decrease in pH and UCS of Continuous Grade RCA Material with 0% Added Cement

Curing Time [days]	pH-value		UCS [Mpa]	
	Non-Carbonated	Carbonated	Non-Carbonated	Carbonated
1	11.7	9.79	2.25	1.12
7	12.11	9.57	2.03	1.65

Indeed, an understanding of how the results obtained from accelerated lab carbonation compare to those expected as a consequence of environmental carbonation is necessary. The laboratory allowed for a concentration of 100 000 ppm (10%) of CO_2, which is aggressive when compared to the 0.03% CO_2 present in the environment (air). However, the percentage of CO_2 located within soil depths underground can be significantly higher in orders of magnitude, as depicted in Figure 6-3, and is furthermore influenced by the climatic region.

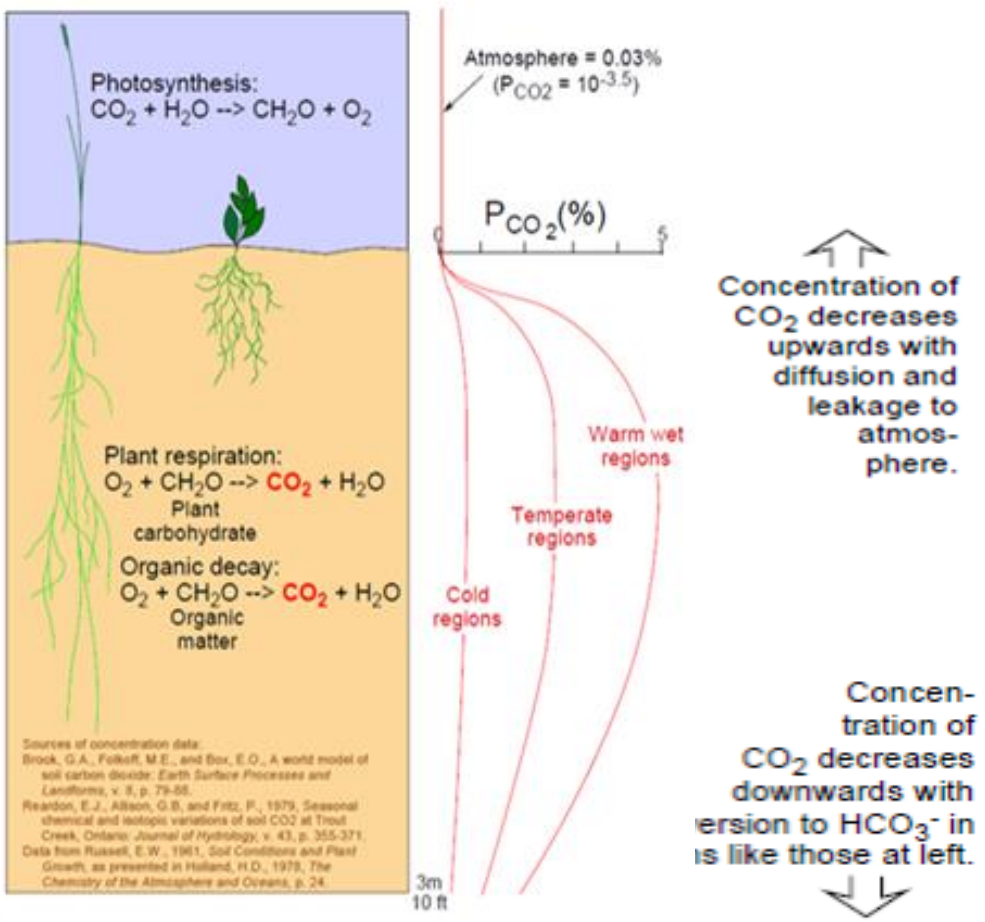


Figure 6-3: Pavement life non-carbonated vs Carbonated (Railsback, 2006)

This suggests that the application of 10% CO_2 concentration, under accelerated lab conditions, is not entirely excessive. In perspective, the rate at which the carbonation depth can proceed, at a CO_2 concentration of 3.0%, is illustrated in Figure 6-4.

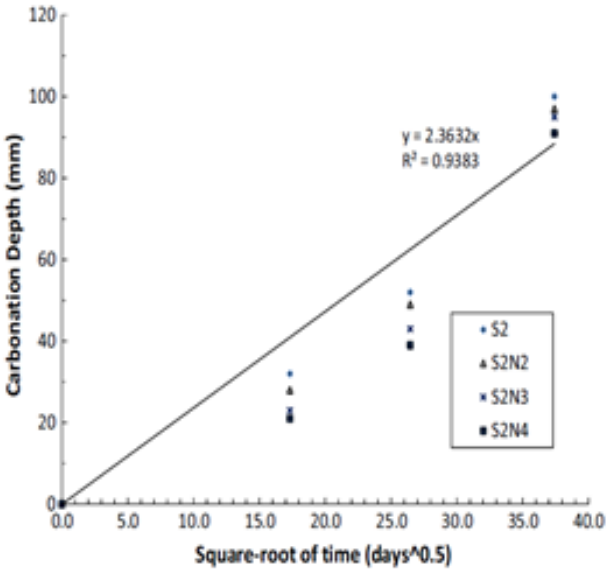


Figure 6-4: Estimated Depth of Ambient Carbonation vs Square Root of Time (RH=50%; CO2 = 3%) (Rezagholilou, Papadakis and Nikraz (2017))

Figure 6-4 illustrates that material exposed for a period of 4weeks (with RH of 50%) resulted in a carbonation depth of 16mm. This implies that approximately 10% of a typical layer depth of (150-200mm) could be compromised by the effects of carbonation.

These results, in combination with the susceptibility (as shown through the decrease in the pH) to carbonation, as shown through the current research study, for specifically lighter stabilised materials, could be detrimental for such layer.

To put the concern of carbonation into context, the following arguments are brought forward:

- The current approach for measuring and/or designing for the performance of RCA and RCM (Recycled Concrete Masonry) materials follows the same approach applied to granular materials. This implies that the performance of RCA and RCM material is assumed to be dependent on the stress condition thereof (i.e. deviator stress and stress confinement, etc).
- Due to no formalised processes in place for the use of alternative materials and the fact that these materials are seemingly unregulated in industry, it is quite possible that properties of material processed from extraction to crushing to compacting could be very different. For example, it is possible that a concrete road earmarked for demolition could very well be used elsewhere in roads nearby, thereby ensuring a swift extraction to placement process. This implies that self-cementing of RCA material in such scenario could be much higher due to this material not being exposed to the environment for extended periods of time before utilisation.
- As mentioned earlier, the current design process involves an approach based on granular materials. This implies that either empirical strength tests, such as the California Bearing Ratio, CBR, (as part of the larger set of standard tests), or more detailed tests, such as triaxial, are requested at the time of extracting the material.

- As a result of the presence of latent cement, manifested as self-cementing properties, the results of these tests could appear higher at the time of testing compared to that achieved during the material lifetime.
- Furthermore, placement of the material, specifically as a granular material, will not include typical curing practices associated with stabilised material. The lack of applied curing method will result in the loss of integrity of the initial test results.

In summary, scenarios do exist that subject RCA material to be susceptible durability issues, especially when this material is accepted as a granular material and handled accordingly. It is therefore recommended that guidelines for the use of RCA include pre-processing of the material before use, in order to mitigate this risk. In other words, induce the carbonation process within the material through environmental exposure, prior to initial processing and use of the material. This is advantageous in that tests performed following processing of the material will be more reflective of the subsequent long-term behaviour of the material.

In addition to further reducing this risk, RCA material should not be utilised in the base layer where the highest stresses and strains occur, particularly in the South African environment, where the base layer is positioned high up in the pavement structure.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

The aim of this chapter is to summarise the conclusions made from the research. This is done by discussion the conclusions at hand of the objectives.

Understanding the intrinsic and extrinsic factors that contribute to the carbonation process in order to develop an understanding of how these mechanisms manifest within the pavement layer.

- Literature revealed that the extrinsic factors have significant effect on the degree of carbonation. Factors such as gas pressure and CO_2 concentration were prioritised.
- This study was successful in isolating the intrinsic variables cement, moisture, density and pH. The research revealed that intrinsic variables alone do have an influence on carbonation and therefore, industry should be mindful of these material characteristics.

Investigate and develop a method that would simulate carbonation, under accelerated laboratory conditions, in order to investigate the influence of various variables on carbonation and furthermore evaluate the effect of carbonation on RCA.

- An appropriate carbonation method was developed by investigating current procedures and employing various methods to attain the most appropriate for the current research study.
- In the analysis of a methodical method, the results revealed the importance of accurately measuring extrinsic variables in order to control and normalise these under testing conditions.

To analyse results and determine how carbonation influences strength characteristics of pavement materials.

- The carbonation results revealed that RCA material with 0% added cement, readily carbonates regardless of the curing time and grading of the material. These results allude to lightly cemented materials being more susceptible to carbonation.
- RCA material with 2% added cement showed more resistance to carbonation, however, this resistance declined as curing time increased. Furthermore, the continuous grade RCA material exhibiting a higher resistance to carbonation than the gap grade RCA.

To develop correlations between the governing variables and carbonation of RCA material and ultimately identify how carbonation influences the pavement life of a material.

- The inspection of the results revealed that the variables showed no apparent correlation when considered independent of each other and in their linear state.
- Further analysis, considering these variables as interdependent and non-linear, resulted in correlations between the variables and the UCS strength parameter (used to measure carbonation).

- The considered variables have different influences at various times of the evolution in strength (increased curing days) when considering carbonation.

The main objective of this research study is to gain better insight of the influence of carbonation on stabilised material and/or material that has the potential to stabilise due to latent cementitious product present within the material:

- The relationship between ITS and UCS is stochastic in nature, depending the curing time. This is a consequence of the prominence of different variables governing at different times of strength development of the material.
- Considering these relationships in combination with the observed average decrease and/or increase in UCS from lab data, as a result of carbonation, revealed that carbonation could have a significant influence on pavement life. Furthermore, these results exposed the fact that particular attention should be given to the grading of RCA.
- Considering the primary objective of this research study as being the concern of the impact which materials with self-cementing potential could have on influencing the pavement life, the results are convincing. The results in all different evaluation methods (visual, methodical analysis and pavement life) revealed that lightly cemented materials (represented by RCA with 0% added cement in this research study) are irrefutably susceptible to carbonation. Hence, serious consideration should be taken when using this material and the following suggestions are brought forward:

    - ✓ Processing of RCA when stockpiled should be included in the streamlining of this material.
    - ✓ It is understood that in the application of RCA it is generally handled as a granular material, however, testing of this material as that of a granular could result in conservative results and adjustments to the quality procedures should be employed to ensure proper representation of the continuous performance of the material.
    - ✓ Due to the potential susceptibility of RCA to carbonation it is suggested that the material is applied as a subbase layer, specifically on high profile roads (Category A and B). This is especially important in South Africa where the base layer is positioned high up in the pavement structure due to a thin asphalt layer applied as surfacing. The application of RCA as a subbase layer will mitigate risk of carbonation in the case where incorrect quality processes are implemented.

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APPENDIX A: ACCELERATED LAB CARBONATION DATA

This appendix presents the summarised data obtained for each carbonation chamber. Red text indicates that the data for that specific chamber is incomplete and an average of what was available is presented. Missing data indicates that the data analogue failed to log the data for that specific data for example, the continuous grade RCA UCS specimens which were carbonated together.

Furthermore, the data label ‘Carbonated with’ implies the following:

1. ‘UCS’ refers to two UCS specimens of 0% and 2% addition of cement, respectively, were placed together in a single carbonation chamber. For every curing time and material grading, the 0% cement UCS specimen was placed in the left hand side with the 2% cement UCS specimen on the right hand side of the chamber.

2. ‘All’ refers to a UCS, ITS and Permeability (Perm) specimen with the same addition of cement were placed together in a single carbonation chamber. In each case, the UCS specimen was placed on the left hand side of the carbonation chamber with the permeability specimen placed upon the ITS specimen on the right hand side of the carbonation chamber.

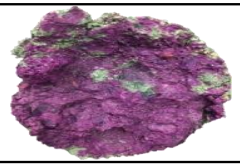
Summary of Chamber Data: Continuous Grade RCA													
Curing Time [Days]	Cement Content [%]	Specimen		Chamber Details		Vacuum Phase				Gas Inlet Phase			
		Type	Code	#	Carbonated with	Pressure [kPa]	Temp [°C]	Relative Humidity	Carbon Dioxide	Pressure (kPa)	Temp [°C]	Relative Humidity	Carbon Dioxide
1	0	UCS	UOC-1-0-4	1	UCS								
			UOC-1-0-5	2	UCS								
			UOC-1-0-6	3	UCS								
	2	UCS	UOC-1-2-7	1	UCS								
			UOC-1-2-8	2	UCS								
			UOC-1-2-9	3	UCS								
	0	UCS	UOC-1-0-1	1	All	4	22.6	73	504	118	22.6	14	99795
		Perm	POC-1-0-4		All	4	22.6	73	504	118	22.6	14	99795
		ITS	TOC-1-0-1		All	4	22.6	73	504	118	22.6	14	99795
		UCS	UOC-1-0-2	2	All	6	22.1	76	788	119	22.4	10	100122
		Perm	POC-1-0-5		All	6	22.1	76	788	119	22.4	10	100122
		ITS	TOC-1-0-2		All	6	22.1	76	788	119	22.4	10	100122
		UCS	UOC-1-0-3	3	All	3	23.6	15	1125	117	23.2	3	99663
		Perm	POC-1-0-6		All	3	23.6	15	1125	117	23.2	3	99663
		ITS	TOC-1-0-3		All	3	23.6	15	1125	117	23.2	3	99663
	2	UCS	UOC-1-2-4	1	All	4	23.8	67	130	119	24.3	8	97760
		Perm	POC-1-2-4		All	4	23.8	67	130	119	24.3	8	97760
		ITS	TOC-1-2-4		All	4	23.8	67	130	119	24.3	8	97760
		UCS	UOC-1-2-5	2	All	6	23.7	73	170	122	24.1	9	100138
		Perm	POC-1-2-5		All	6	23.7	73	170	122	24.1	9	100138
		ITS	TOC-1-2-5		All	6	23.7	73	170	122	24.1	9	100138
		UCS	UOC-1-2-6	3	All	3	25.0	18	223	120	24.3	2	99724
		Perm	POC-1-2-6		All	3	25.0	18	223	120	24.3	2	99724
		ITS	TOC-1-2-6		All	3	25.0	18	223	120	24.3	2	99724
7	0	UCS	UOC-7-0-13	1	UCS	4	23.3	68	128	120	23.7	9	99746
			UOC-7-0-14	2	UCS	6	23.2	64	161	120	23.5	7	100123
			UOC-7-0-15	3	UCS	3	23.8	11	294	119	23.9	1	99765
	2	UCS	UOC-7-2-7	1	UCS	4	23.3	68	128	120	23.7	9	99746
			UOC-7-2-8	2	UCS	6	23.2	64	161	120	23.5	7	100123
			UOC-7-2-9	3	UCS	3	23.8	11	294	119	23.9	1	99765
	0	UCS	UOC-7-0-10	1	All	4	21.9	66	768	119	22.1	9	99899
		Perm	POC-7-0-4		All	4	21.9	66	768	119	22.1	9	99899
		ITS	TOC-7-0-6		All	4	21.9	66	768	119	22.1	9	99899
		UCS	UOC-7-0-11	2	All	6	21.7	71	1012	122	22.0	9	100179
		Perm	POC-7-0-6		All	6	21.7	71	1012	122	22.0	9	100179
		ITS	TOC-7-0-5		All	6	21.7	71	1012	122	22.0	9	100179
		UCS	UOC-7-0-12	3	All	4	22.5	8	1415	119	22.3	2	99819
		Perm	POC-7-0-5		All	4	22.5	8	1415	119	22.3	2	99819
		ITS	TOC-7-0-4		All	4	22.5	8	1415	119	22.3	2	99819
	2	UCS	UOC-7-2-10	1	All	4	22.7	61	478	117	23.2	12	99762
		Perm	POC-7-2-6		All	4	22.7	61	478	117	23.2	12	99762
		ITS	TOC-7-2-4		All	4	22.7	61	478	117	23.2	12	99762
		UCS	UOC-7-2-11	2	All	6	22.6	64	542	121	22.9	9	100130
		Perm	POC-7-2-5		All	6	22.6	64	542	121	22.9	9	100130
		ITS	TOC-7-2-5		All	6	22.6	64	542	121	22.9	9	100130
		UCS	UOC-7-2-12	3	All	3	23.1	18	977	120	23.3	3	99789
		Perm	POC-7-2-4		All	3	23.1	18	977	120	23.3	3	99789
		ITS	TOC-7-2-6		All	3	23.1	18	977	120	23.3	3	99789
28	0	UCS	UOC-28-0-3	1	UCS	4	23.2	25	650	117	23.4	2	99729
			UOC-28-0-1	2	UCS	7	22.4	69	541	122	22.8	9	100144
			UOC-28-0-2	3	UCS	4	23.0	70	538	117	22.6	11	99913
	2	UCS	UOC-28-2-6	1	UCS	4	23.2	25	650	117	23.4	2	99729
			UOC-28-2-4	2	UCS	7	22.4	69	541	122	22.8	9	100144
			UOC-28-2-5	3	UCS	4	23.0	70	538	117	22.6	11	99913
	0	UCS	UOC-28-0-4	1	All	9	23.8	63	1332	114	23.9	12	99662
		Perm	POC-28-0-4		All	9	23.8	63	1332	114	23.9	12	99662
		ITS	TOC-28-0-3		All	9	23.8	63	1332	114	23.9	12	99662
		UCS	UOC-28-0-5	2	All	10	23.3	57	1800	119	23.7	7	100109
		Perm	POC-28-0-5		All	10	23.3	57	1800	119	23.7	7	100109
		ITS	TOC-28-0-2		All	10	23.3	57	1800	119	23.7	7	100109
		UCS	UOC-28-0-6	3	All	7	24.5	22	2672	120	24.5	1	99721
		Perm	POC-28-0-6		All	7	24.5	22	2672	120	24.5	1	99721
		ITS	TOC-28-0-1		All	7	24.5	22	2672	120	24.5	1	99721
	2	UCS	UOC-28-2-7	1	All	5	22.4	66	843	120	22.7	8	99693
		Perm	POC-28-2-4		All	5	22.4	66	843	120	22.7	8	99693
		ITS	TOC-28-2-2		All	5	22.4	66	843	120	22.7	8	99693
		UCS	UOC-28-2-8	2	All	7	22.0	72	862	122	22.4	7	100128
		Perm	POC-28-2-5		All	7	22.0	72	862	122	22.4	7	100128
		ITS	TOC-28-2-1		All	7	22.0	72	862	122	22.4	7	100128
		UCS	UOC-28-2-9	3	All	4	23.1	22	625	119	23.2	3	99753
		Perm	POC-28-2-6		All	4	23.1	22	625	119	23.2	3	99753
		ITS	TOC-28-2-3		All	4	23.1	22	625	119	23.2	3	99753
					Mean	5	23.0	51	809	119	23.2	7	99794
					Median	4	23.1	64	709	119	23.2	8	99792
					StdDev	2	0.8	24	595	2	0.7	4	484
					Skewness	1	0.4	-1	1	-1	0.1	0	-3

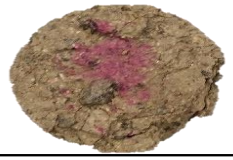
Figure 7-1: Summary of environmental chamber data for accelerated lab carbonation of continuous grade RCA

Summary of Chamber Data: Gap Grade RCA													
Curing Time [Days]	Cement Content [%]	Specimen		Chamber Details		Vacuum Phase				Gas Inlet Phase			
		Type	Code	#	Carbonated with	Pressure [kPa]	Temp [°C]	Relative Humidity	Carbon Dioxide	Pressure (kPa)	Temp [°C]	Relative Humidity	Carbon Dioxide (ppm)
1	0	UCS											
	2	UCS	UOG-1-2-4	1	UCS	4	22	69	213	76	22	25	65593
			UOG-1-2-5	2	UCS	6	22	71	141	79	22	22	66741
			UOG-1-2-6	3	UCS	23	4	52	187	#DIV/0!	#DIV/0!	20	67245
	0	UCS	UOG-1-0-1	1	All	4	22.3	75	207	117	22.1	14	99788
		Perm	POG-1-0-1		All	4	22.3	75	207	117	22.1	14	99788
		ITS	TOG-1-0-1		All	4	22.3	75	207	117	22.1	14	99788
		UCS	UOG-1-0-2	2	All	6	21.8	83	333	121	21.9	12	100144
		Perm	POG-1-0-2		All	6	21.8	83	333	121	21.9	12	100144
		ITS	TOG-1-0-2		All	6	21.8	83	333	121	21.9	12	100144
		UCS	UOG-1-0-3	3	All	3	22.6	-11	137	0	22.6	-26	20
		Perm	POG-1-0-3		All	3	22.6	-11	137	0	22.6	-26	20
		ITS	TOG-1-0-3		All	3	22.6	-11	137	0	22.6	-26	20
	2	UCS	UOG-1-2-8	1	All	4	22.9	45	782	115	23.1	7	99497
		Perm	POG-1-2-4		All	4	22.9	45	782	115	23.1	7	99497
		ITS	TOG-1-2-3		All	4	22.9	45	782	115	23.1	7	99497
		UCS	UOG-1-2-9	2	All	7	21.6	68	908	118	22.1	14	100034
		Perm	POG-1-2-3		All	7	21.6	68	908	118	22.1	14	100034
		ITS	TOG-1-2-2		All	7	21.6	68	908	118	22.1	14	100034
		UCS	UOG-1-2-7	3	All	5	21.9	62	1033	117	22.2	8	100098
		Perm	POG-1-2-5		All	5	21.9	62	1033	117	22.2	8	100098
		ITS	TOG-1-2-1		All	5	21.9	62	1033	117	22.2	8	100098
7	0	UCS	UOG-7-0-1	1	UCS	3	22.6	6	849	104	23.2	-1	87596
			UOG-7-0-2	2	UCS	5	21.9	65	608	117	22.4	14	100102
			UOG-7-0-3	3	UCS	7	21.7	67	1323	121	22.3	10	100046
	2	UCS	UOG-7-2-4	1	UCS	3	22.6	6	849	104	23.2	-1	87596
			UOG-7-2-5	2	UCS	5	21.9	65	608	117	22.4	14	100102
			UOG-7-2-6	3	UCS	7	21.7	67	1323	121	22.3	10	100046
	0	UCS	UOG-7-0-6	1	All	4	23.5	47	438	117	23.9	3	99564
		Perm	POG-7-0-6		All	4	23.5	47	438	117	23.9	3	99564
		ITS	TOG-7-0-6		All	4	23.5	47	438	117	23.9	3	99564
		UCS	UOG-7-0-5	2	All	7	23.0	70	458	120	22.9	8	100052
		Perm	POG-7-0-5		All	7	23.0	70	458	120	22.9	8	100052
		ITS	TOG-7-0-5		All	7	23.0	70	458	120	22.9	8	100052
		UCS	UOG-7-0-4	3	All	5	23.3	66	497	117	23.1	9	100090
		Perm	POG-7-0-3		All	5	23.3	66	497	117	23.1	9	100090
		ITS	TOG-7-0-4		All	5	23.3	66	497	117	23.1	9	100090
	2	UCS	UOG-7-2-9	1	All	6	21.5	60	1769	119	21.8	10	99824
		Perm	POG-7-2-10		All	6	21.5	60	1769	119	21.8	10	99824
		ITS	TOG-7-2-6		All	6	21.5	60	1769	119	21.8	10	99824
		UCS	UOG-7-2-8	2	All	8	21.3	66	1949	113	21.5	15	100158
		Perm	POG-7-2-9		All	8	21.3	66	1949	113	21.5	15	100158
		ITS	TOG-7-2-5		All	8	21.3	66	1949	113	21.5	15	100158
		UCS	UOG-7-2-7	3	All	5	22.0	30	1499	119	22.3	3	99804
		Perm	POG-7-2-3		All	5	22.0	30	1499	119	22.3	3	99804
		ITS	TOG-7-2-4		All	5	22.0	30	1499	119	22.3	3	99804
28	0	UCS	UOG-28-0-4	1	UCS	7	22.9	77	531	120	22.2	12	100150
			UOG-28-0-6	2	UCS	4	22.6	46	685	119	22.9	2	99746
			UOG-28-0-5	3	UCS	4	23.8	73	609	119	22.2	16	99932
	2	UCS	UOG-28-2-4	1	UCS	7	22.9	77	531	120	22.2	12	100150
			UOG-28-2-6	2	UCS	4	22.6	46	685	119	22.9	2	99746
			UOG-28-2-5	3	UCS	4	23.8	73	609	119	22.2	16	99932
	0	UCS	UOG-28-0-7	1	All	4	24.9	72	511	119	24.1	13	99835
		Perm	POG-28-0-12		All	4	24.9	72	511	119	24.1	13	99835
		ITS	TOG-28-0-4		All	4	24.9	72	511	119	24.1	13	99835
		UCS	UOG-28-0-8	2	All	7	24.7	81	537	121	24.0	15	100153
		Perm	POG-28-0-13		All	7	24.7	81	537	121	24.0	15	100153
		ITS	TOG-28-0-5		All	7	24.7	81	537	121	24.0	15	100153
		UCS	UOG-28-0-9	3	All	4	24.6	41	758	119	24.6	3	99773
		Perm	POG-28-0-14		All	4	24.6	41	758	119	24.6	3	99773
		ITS	TOG-28-0-6		All	4	24.6	41	758	119	24.6	3	99773
	2	UCS	UOG-28-2-1	1	All	6	23.3	70	551	51	22.2	23	61706
		Perm	POG-28-2-6		All	6	23.3	70	551	51	22.2	23	61706
		ITS	TOG-28-2-4		All	6	23.3	70	551	51	22.2	23	61706
		UCS	UOG-28-2-2	2	All	4	22.4	19	767	91	23.1	8	62654
		Perm	POG-28-2-10		All	4	22.4	19	767	91	23.1	8	62654
		ITS	TOG-28-2-5		All	4	22.4	19	767	91	23.1	8	62654
		UCS	UOG-28-2-3	3	All	4	21.6	22	64	93	21.9	14	28715
		Perm	POG-28-2-13		All	4	21.6	22	64	93	21.9	14	28715
		ITS	TOG-28-2-6		All	4	21.6	22	64	93	21.9	14	28715
					Mean	5	22.4	54	715	107	22.7	9	87398
					Median	5	22.6	66	551	117	22.4	10	99824
					StdDev	3	2.5	24	490	28	0.8	10	26159
					Skewness	5	-6.2	-1	1	-3	0.8	-2	-2
					Mean	5	22.4	54	715	111	22.4	11	91468
(Data in red ommitted)					**Median**	5	22.6	66	551	117	22.2	10	99878
					StdDev	3	2.5	24	490	17	0.6	5	19825
					Skewness	5	-6.2	-1	1	-3	0.8	0	-2

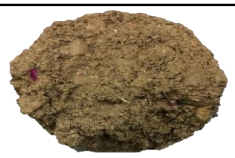
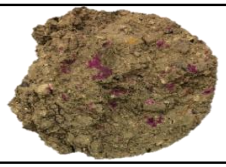
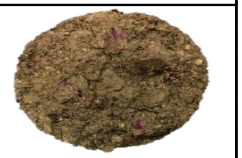
Figure 7-2: Summary of environmental chamber data for accelerated lab carbonation of gap grade RCA

APPENDIX B: RESULTS AND IMAGES OF CARBONATED SPECIMENS

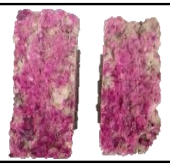
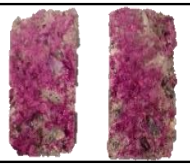
1day Gap-UCS 0% & 2%						
SPECIMEN PICTURES	N/A		N/A		N/A	
Specime Type	UCS (0%)	UCS (2%)	UCS (0%)	UCS (2%)	UCS (0%)	UCS (2%)
Specimen Code		UOG-1-2-4		UOG-1-2-5		UOG-1-2-6
Strength		4.25		4.34		4.63
pH (retained Moisture-		12.23		12.22		12.29
Mass Change (%)		-0.11%		-0.12%		-0.11%
Carbonation (%)		10%		55%		5%

7day Gap-UCS 0% & 2%						
SPECIMEN PICTURES						
Specime Type	UCS (0%)	UCS (2%)	UCS (0%)	UCS (2%)	UCS (0%)	UCS (2%)
Specimen Code	UOG-7-0-1	UOG-7-2-4	UOG-7-0-2	UOG-7-2-5	UOG-7-0-3	UOG-7-2-6
Strength	1.92	5.45	1.94	5.26	1.85	5.06
pH (retained Moisture-	9.81	11.01	9.35	10.60	9.96	10.64
Mass Change (%)	0.20%	0.11%	0.24%	0.16%	0.17%	0.14%
Carbonation (%)	90%	15%	80%	60%	90%	15%

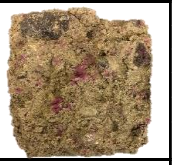
28day Gap-UCS 0% & 2%

SPECIMEN PICTURES						
Specime Type	**UCS (0%)**	**UCS (2%)**	**UCS (0%)**	**UCS (2%)**	**UCS (0%)**	**UCS (2%)**
Specimen Code	UOG-28-0-4	UOG-28-2-4	UOG-28-0-6	UOG-28-2-6	UOG-28-0-5	UOG-28-2-5
Strength	1.70	3.58	1.49	3.03	1.48	3.38
pH (retained Moisture-	8.96	9.74	8.89	9.54	8.93	9.63
Mass Change (%)	0.36%	0.45%	0.33%	0.48%	0.35%	0.51%
Carbonation (%)	95%	90%	95%	90%	95%	90%

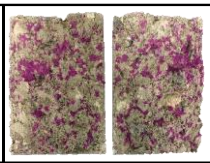
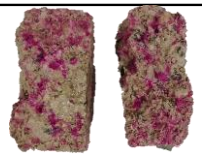
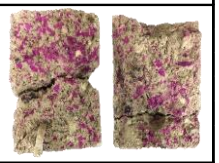
1day Gap -UCS-ITS-PERM0%

SPECIMEN PICTURES									
Specime Type	**UCS**	**PERMEABILITY**	**ITS**	**UCS**	**PERMEABILITY**	**ITS**	**UCS**	**PERMEABILITY**	**ITS**
Specimen Code	UOG-1-0-1	POG-1-0-1	TOG-1-0-1	UOG-1-0-2	POG-1-0-2	TOG-1-0-2	UOG-1-0-3	POG-1-0-3	TOG-1-0-3
Strength	1.02	69.71 None	34.55	1.06	76.71 None	34.49	1.27	75.92 None	34.20
pH (retained Moisture-	8.58	0.7% 1.33	-	8.53	0.6% 0.33	-	8.94	0.6% 1.33	-
Mass Change (%)	0.20%	0.28% 1.00	0.13%	0.12%	0.37% 1.00	0.13%	0.13%	0.26% 2.33	0.14%
Carbonation (%)	95.00%	65.00% 1.67	85.00%	95.00%	10.00% 1.67	95.00%	95.00%	20.00% 2.33	90.00%

7day Gap-UCS-ITS-PERM0%

SPECIMEN PICTURES		NO PICTURES			NO PICTURES			NO PICTURES	
Specime Type	**UCS**	**PERMEABILITY**	**ITS**	**UCS**	**PERMEABILITY**	**ITS**	**UCS**	**PERMEABILITY**	**ITS**
Specimen Code	UOG-7-0-6	POG-7-0-6	TOG-7-0-6	UOG-7-0-5	POG-7-0-5	TOG-7-0-5	UOG-7-0-4	POG-7-0-3	TOG-7-0-4
Strength	1.76	75.92 None	84.38	1.86	76.71 None	75.93	1.78	69.71 None	69.80
pH (retained Moisture-	9.15	0.6% 11.67	-	9.25	0.6% 8.00	-	9.29	0.7% 5.67	-
Mass Change (%)	0.23%	0.22% 10.67	0.27%	0.25%	0.22% 9.00	0.26%	0.24%	0.26% 13.67	0.25%
Carbonation (%)	95.00%	0.00% 22.67	75.00%	95.00%	0.00% 20.67	85.00%	95.00%	0.00% 10.67	90.00%

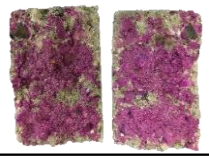
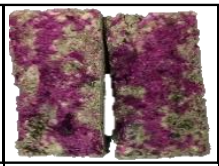
28day Gap-UCS-ITS-PERM0%

SPECIMEN PICTURES									
Specime Type	UCS	PERMEABILITY	ITS	UCS	PERMEABILITY	ITS	UCS	PERMEABILITY	ITS
Specimen Code	UOG-28-0-7	POG-28-0-12	TOG-28-0-4	UOG-28-0-8	POG-28-0-13	TOG-28-0-5	UOG-28-0-9	POG-28-0-14	TOG-28-0-6
Strength	3.39	293.32 Did Not break	362.12	3.37	251.15 Did Not break	381.86	2.91	291.57 ot be tested at 2 bar as	392.68
pH (retained Moisture-	9.75	2.2% 92.13	-	10.14	2.6% 70.47	-	10.05	2.7% 154.12	-
Mass Change (%)	0.42%	0.41% 96.08	0.35%	0.42%	0.42% 126.03	0.32%	0.40%	0.45% 273.10	0.37%
Carbonation (%)	95.00%	60.00% 104.58	75.00%	95.00%	60.00% 165.13	70.00%	95.00%	65.00% 0.00	70.00%

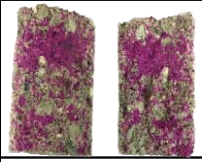
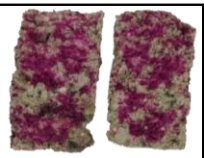
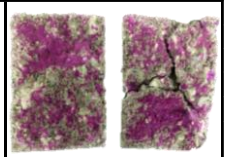
1day Gap-UCS-ITS-PERM2%

SPECIMEN PICTURES									
Specime Type	UCS	PERMEABILITY	ITS	UCS	PERMEABILITY	ITS	UCS	PERMEABILITY	ITS
Specimen Code	UOG-1-2-8	POG-1-2-4	TOG-1-2-3	UOG-1-2-9	POG-1-2-3	TOG-1-2-2	UOG-1-2-7	POG-1-2-5	TOG-1-2-1
Strength	4.98	166.27 None	532.91	4.26	468.71 None	516.01	5.07	520.91 None	421.79
pH (retained Moisture-	11.30	0.7% 0.33	-	11.75	0.7% 0.07	-	11.70	0.8% 0.47	-
Mass Change (%)	0.04%	0.05% 0.33	0.09%	0.08%	0.06% 0.13	0.08%	0.00%	0.04% 0.13	0.02%
Carbonation (%)	10.00%	20.00% 0.07	45.00%	20.00%	1.00% 0.47	60.00%	10.00%	10.00% 0.07	10.00%

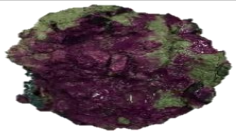
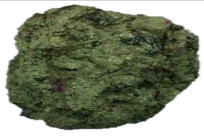
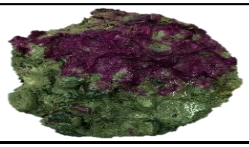
7day Gap-UCS-ITS-PERM2%

SPECIMEN PICTURES									
Specime Type	UCS	PERMEABILITY	ITS	UCS	PERMEABILITY	ITS	UCS	PERMEABILITY	ITS
Specimen Code	UOG-7-2-9	POG-7-2-10	TOG-7-2-6	UOG-7-2-8	POG-7-2-9	TOG-7-2-5	UOG-7-2-7	POG-7-2-3	TOG-7-2-4
Strength	4.78	468.71 None	590.90	3.65	682.77 None	696.40	4.98	#VALUE! None	651.96
pH (retained Moisture-	10.81	0.7% 0.33	-	10.43	0.01 0.47	-	10.19	0.01 0.00	-
Mass Change (%)	0.23%	0.23% 0.00	0.22%	0.33%	0.26% 0.00	0.21%	0.23%	0.02% 0.13	0.13%
Carbonation (%)	65.00%	15.00% 0.00	25.00%	80.00%	55.00% 0.33	10.00%	70.00%	10.00% 0.13	10.00%

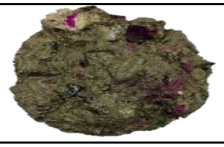
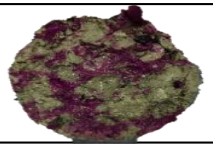
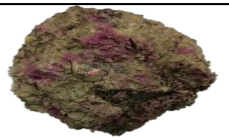
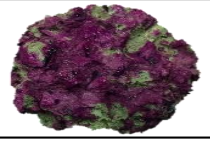
28day Gap-UCS-ITS-PERM2%

SPECIMEN PICTURES									
Specime Type	UCS	PERMEABILITY	ITS	UCS	PERMEABILITY	ITS	UCS	PERMEABILITY	ITS
Specimen Code	UOG-28-2-1	POG-28-2-6	TOG-28-2-4	UOG-28-2-2	POG-28-2-10	TOG-28-2-5	UOG-28-2-3	POG-28-2-13	TOG-28-2-6
Strength	3.17	328.90 Did Not break	817.13	3.07	863.57 Did Not break	754.63	2.96	663.84 Did Not break	851.80
pH (retained Moisture-	9.62	1.8% 24.19	-	9.70	1.8% 110.05	-	9.83	1.7% 84.91	-
Mass Change (%)	0.61%	0.37% 25.60	0.44%	0.58%	0.49% 117.07	0.49%	0.55%	0.52% 99.45	0.43%
Carbonation (%)	95.00%	25.00% 26.77	60.00%	95.00%	60.00% 112.08	70.00%	95.00%	55.00% 114.07	60.00%

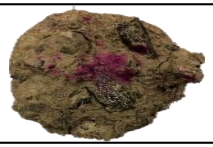
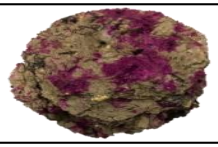
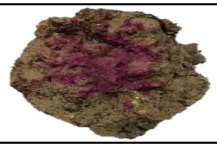
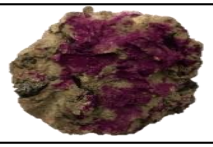
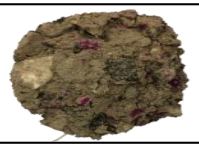
1day Continuous-UCS 0% & 2%

SPECIMEN PICTURES						
Specime Type	UCS	UCS	UCS	UCS	UCS	UCS
Specimen Code	UOC-1-0-4	UOC-1-2-7	UOC-1-0-5	UOC-1-2-8	UOC-1-0-6	UOC-1-2-9
Density	2272.69	2269.39	2276.13	2303.02	2246.51	2270.19
Strength	1.03	3.08	0.95	3.39	1.22	4.40
pH (retained Moisture-Perm)	9.81	11.70	9.84	11.72	9.64	11.21
Mass Change (%)	0.08%	0.03%	0.08%	0.03%	0.07%	0.06%
Carbonation (%)	95%	20%	95%	10%	95%	65%

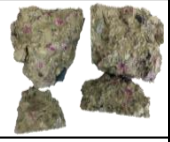
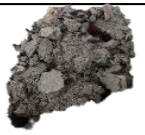
7day Continuous-UCS 0% & 2%

SPECIMEN PICTURES						
Specime Type	**UCS (0%)**	**UCS (2%)**	**UCS (0%)**	**UCS (2%)**	**UCS (0%)**	**UCS (2%)**
Specimen Code	UOC-7-0-13	UOC-7-2-7	UOC-7-0-14	UOC-7-2-8	UOC-7-0-15	UOC-7-2-9
Density	2272.39	2288.41	2267.47	2264.96	2257.88	2285.34
Strength	2.22	4.98	2.44	3.84	1.79	5.88
pH (retained Moisture-Perm)	9.59	10.51	9.50	10.82	9.72	10.63
Mass Change (%)	0.12%	0.05%	0.12%	0.06%	0.06%	0.04%
Carbonation (%)	85%	65%	90%	70%	80%	10%

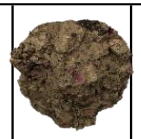
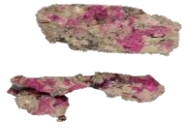
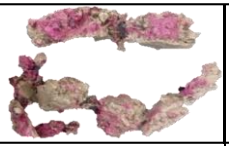
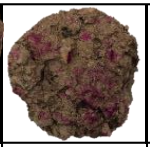
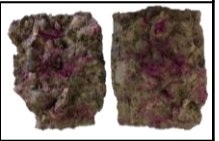
28day Continuous-UCS 0% & 2%

SPECIMEN PICTURES						
Specime Type	**UCS (0%)**	**UCS (2%)**	**UCS (0%)**	**UCS (2%)**	**UCS (0%)**	**UCS (2%)**
Specimen Code	UOC-28-0-3	UOC-28-2-6	UOC-28-0-1	UOC-28-2-4	UOC-28-0-2	UOC-28-2-5
Density	2269.04	2296.04	2223.82	2230.29	2246.83	2285.06
Strength	2.00	5.66	1.55	4.84	1.91	6.01
pH (retained Moisture-Perm)	9.64	10.81	10.25	10.70	9.68	11.12
Mass Change (%)	0.26%	0.25%	0.28%	0.34%	0.31%	0.25%
Carbonation (%)	85%	65%	65%	45%	90%	65%

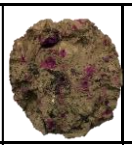
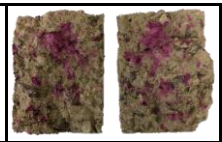
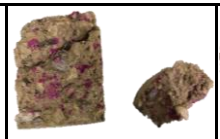
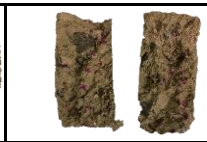
1day Continuous -UCS-ITS-PERM0%

SPECIMEN PICTURES									
Specime Type	UCS	PERMEABILITY		ITS	UCS	PERMEABILITY		ITS	UCS	PERMEABILITY		ITS
Specimen Code	UOC-1-0-1	POC-1-0-4		TOC-1-0-1	UOC-1-0-2	POC-1-0-5		TOC-1-0-2	UOC-1-0-3	POC-1-0-6		TOC-1-0-3
Density	2275.70348	2269.867798		2263.096741	2270.610521	2266.36639		2265.440397	2283.731331	2265.41146		2255.014615
Strength	1.12	#VALUE!	Specimen disintegrated after 1 bar	74.43	0.79	9.87	0.00	69.28	1.64	#VALUE!	Specimen disintegrated in bar	76.92
pH (retained Moisture-Perm)	9.77	-11.06%	4.00	-	9.74	-4.32%	1.67	-	9.93	0.80%	2.67	-
Mass Change (%)	0.12%	0.12%	#DIV/0!	0.16%	0.12%	0.18%	2.67	0.16%	0.09%	0.13%	90.67	0.12%
Carbonation (%)	95.00%	95%	#DIV/0!	95.00%	95.00%	95%	3.33	95.00%	85.00%	95%	6.67	90.00%

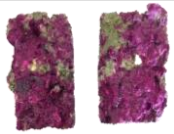
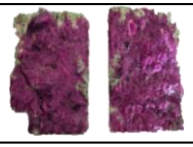
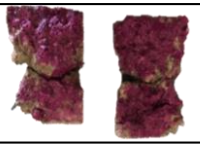
7day Continuous-UCS-ITS-PERM0%

SPECIMEN PICTURES									
Specime Type	UCS	PERMEABILITY		ITS	UCS	PERMEABILITY		ITS	UCS	PERMEABILITY		ITS
Specimen Code	UOC-7-0-10	POC-7-0-4		TOC-7-0-6	UOC-7-0-11	POC-7-0-6		TOC-7-0-5	UOC-7-0-12	POC-7-0-5		TOC-7-0-4
Density	2263.966714	2221.698642		2270.880603	2268.878991	2229.992777		2259.84679	2271.831305	2218.909279		2259.189949
Strength	0.92	18.62	NO SAND	91.85	1.19	#VALUE!	Specimen broke in bar NO SAND	50.64	1.32	109.50	NO SAND	204.53
pH (retained Moisture-Perm)	9.30	0.25%	2.00	-	9.38	0.33%	2.00	-	9.92	1.86%	1.33	-
Mass Change (%)	0.12%	0.06%	4.33	0.12%	0.17%	0.03%	12.00	0.22%	0.15%	0.13%	3.33	0.16%
Carbonation (%)	95.00%	70%	9.00	85.00%	95.00%	70%	19.00	85.00%	70.00%	65%	5.67	70.00%

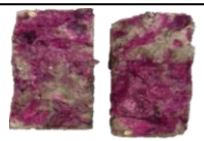
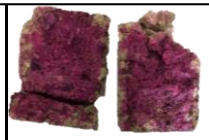
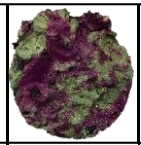
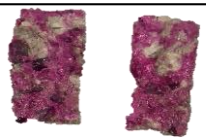
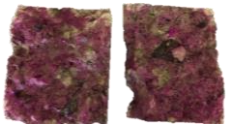
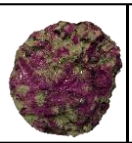
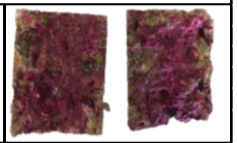
28day Continuous-UCS-ITS-PERM0%

SPECIMEN PICTURES									
Specime Type	UCS	PERMEABILITY		ITS	UCS	PERMEABILITY		ITS	UCS	PERMEABILITY		ITS
Specimen Code	UOC-28-0-4	POC-28-0-4		TOC-28-0-3	UOC-28-0-5	POC-28-0-5		TOC-28-0-2	UOC-28-0-6	POC-28-0-6		TOC-28-0-1
Density	2248.351405	2252.055598		2258.451657	2245.337401	2263.215122		2277.709796	2272.914479	2261.273431		2246.226055
Strength	2.07	#VALUE!	None	123.04	2.58	#VALUE!	None	127.84	2.83	#VALUE!	None	112.80
pH (retained Moisture-Perm)	10.11	1.27%	0.80	-	9.79	1.48%	1.13	-	10.06	1.25%	1.20	-
Mass Change (%)	0.28%	0.33%	1.07	0.27%	0.27%	0.32%	2.00	0.28%	0.23%	0.36%	1.67	0.29%
Carbonation (%)	85.00%	90%	1.67	75.00%	80.00%	90%	5.07	80.00%	80.00%	90%	1.73	80.00%

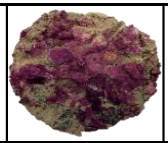
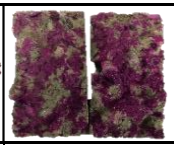
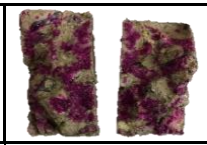
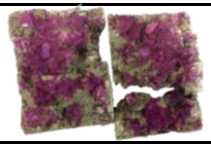
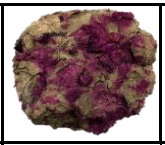
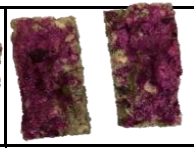
1day Continuous-UCS-ITS-PERM2%

SPECIMEN PICTURES									
Specime Type	UCS	PERMEABILITY		ITS	UCS	PERMEABILITY		ITS	UCS	PERMEABILITY		ITS
Specimen Code	UOC-1-2-4	POC-1-2-4		TOC-1-2-4	UOC-1-2-5	POC-1-2-5		TOC-1-2-5	UOC-1-2-6	POC-1-2-6		TOC-1-2-6
Density	2293.01451	2210.871778		2239.324302	2256.023459	2260.223009		2226.408581	2266.148937	2257.708361		2261.457514
Strength	3.69	99.14	None	344.82	2.67	277.88	None	296.49	3.34	254.17	None	382.90
pH (retained Moisture-Perm)	12.08	0.83%	383.33	-	12.13	0.67%	10.67	-	11.31	0.58%	0.33	-
Mass Change (%)	-0.07%	-0.11%	391.67	-0.01%	-0.03%	-0.03%	9.33	0.03%	-0.01%	-0.07%	0.00	0.01%
Carbonation (%)	10.00%	15%	409.52	15.00%	5.00%	10%	5.00	5.00%	85.00%	1%	0.00	10.00%

7day Continuous-UCS-ITS-PERM2%

SPECIMEN PICTURES									
Specime Type	UCS	PERMEABILITY		ITS	UCS	PERMEABILITY		ITS	UCS	PERMEABILITY		ITS
Specimen Code	UOC-7-2-10	POC-7-2-6		TOC-7-2-4	UOC-7-2-11	POC-7-2-5		TOC-7-2-5	UOC-7-2-12	POC-7-2-4		TOC-7-2-6
Density	2280.17636	2196.954298		2270.764854	2277.198851	2221.072458		2269.503189	2290.118302	2225.487051		2271.459348
Strength	3.72	497.04	Specimen broke in hpp NO SAND	464.67	4.13	547.49	NO SAND	445.69	3.66	409.19	NO SAND	538.46
pH (retained Moisture-Perm)	10.80	0.73%	0.01	-	10.96	0.71%	0.01	-	11.02	0.73%	0.01	-
Mass Change (%)	0.04%	0.07%	0.01	0.09%	0.05%	0.08%	0.01	0.08%	0.06%	0.00%	0.01	0.10%
Carbonation (%)	25.00%	55%	0.01	10.00%	25.00%	60%	0.01	10.00%	10.00%	25%	0.00	15.00%

28day Continuous-UCS-ITS-PERM2%

SPECIMEN PICTURES									
Specime Type	UCS	PERMEABILITY		ITS	UCS	PERMEABILITY		ITS	UCS	PERMEABILITY		ITS
Specimen Code	UOC-28-2-7	POC-28-2-4		TOC-28-2-2	UOC-28-2-8	POC-28-2-5		TOC-28-2-1	UOC-28-2-9	POC-28-2-6		TOC-28-2-3
Density	2267.388296	2279.417095		2268.218374	2247.391013	2234.222309		2264.250735	2298.21137	2268.912869		2272.501089
Strength	7.38	303.49	None	575.97	7.67	580.92	None	709.43	8.45	873.28	None	638.65
pH (retained Moisture-Perm)	11.37	0.79%	0.07	-	11.25	0.94%	0.00	-	11.32	0.59%	0.07	-
Mass Change (%)	0.18%	0.23%	0.07	0.25%	0.18%	0.30%	0.00	0.24%	0.19%	0.20%	0.00	0.25%
Carbonation (%)	60.00%	20%	0.00	50.00%	25.00%	60%	0.00	35.00%	50.00%	10%	0.07	50.00%